SCHOOL OF CIVIL ENGINEERING

JOINT HIGHWAY RESEARCH PROJECT

JHRP-74-12

SOIL STABILIZATION FOR EROSION CONTROL

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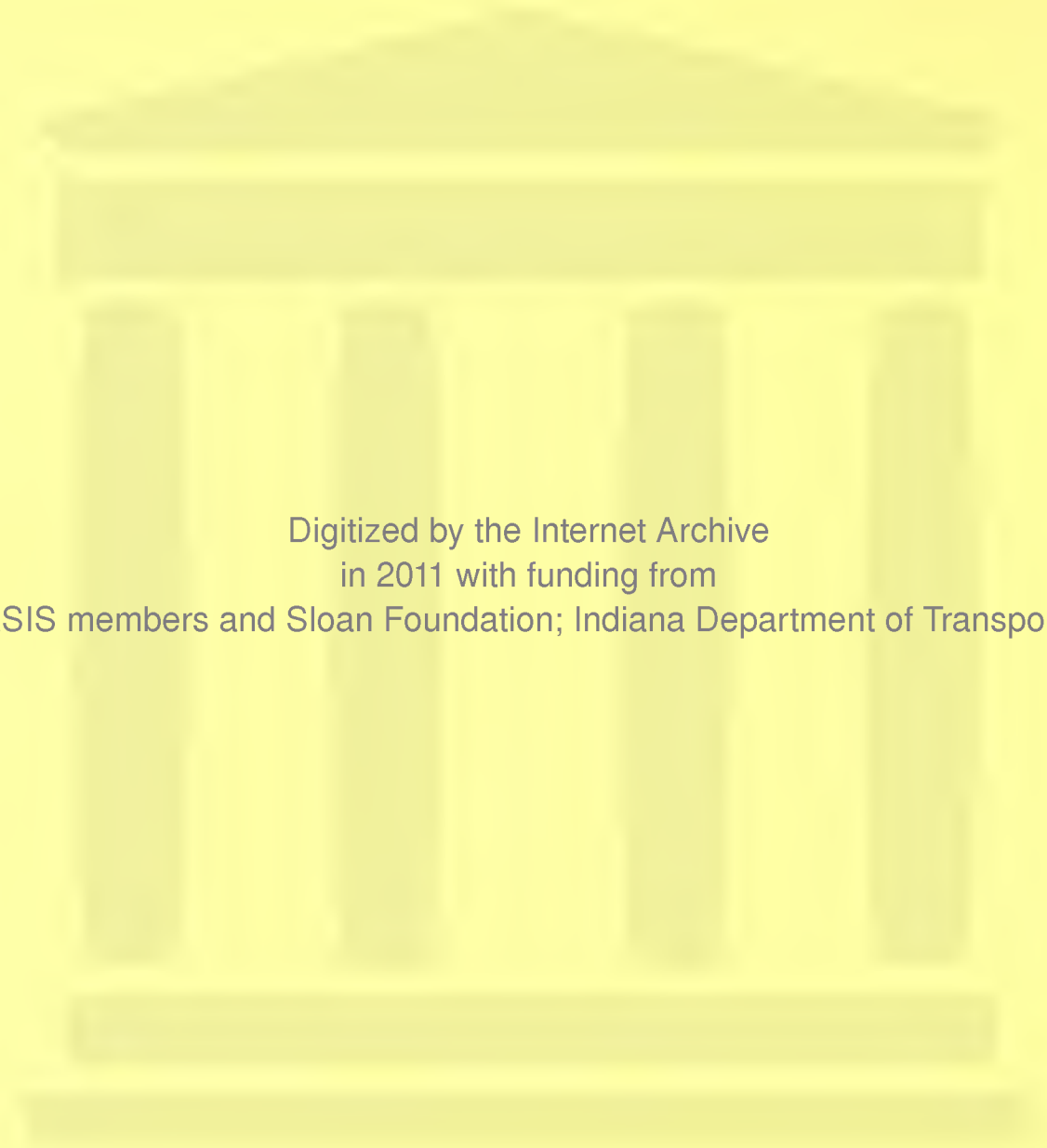

Interim Report

SOIL STABILIZATION FOR EROSION CONTROL

TO: J. F. McLaughlin, Director
Joint Highway Research Project

August 28, 1974

Project: C-36-50H

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

File: 6-19-8

Attached is an Interim Report on the HPR Part II Research Project titled "Soil Stabilization for Erosion Control". The Report also covers this title and has been prepared by Messrs. Sidney Diamond and Mitsunori Kawamura as a summary of the research activities on the project from the beginning in November 1971 until the early summer of 1974.

The Report relates findings to date from the use of small percentages of hydrated lime on Portland cement mixed into the soil surface. The development of a laboratory rainfall simulator for use in the project is also discussed. The findings reported indicate that effective protection against soil erosion through the use of hydrated lime or Portland cement in an inexpensive manner may be possible.

The Report is presented to the Board for information and is continuing.

Respectfully submitted,

Harold L. Michael
Associate Director

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
SOIL STABILIZATION FOR EROSION CONTROL	August 1974
	6. Performing Organization Code: C-36-50H
7. Author(s): Sidney Diamond and Mitsunori Kawamura	8. Performing Organization Report No.: JHRP-74-12
9. Performing Organization Name and Address: Joint Highway Research Project, Civil Engineering Building, Purdue University, W. Lafayette, Indiana 47907	10. Work Unit No.
	11. Contract or Grant No.: HPR-1(11) Part II
12. Sponsoring Agency Name and Address: Indiana State Highway Commission, 100 North Senate Avenue, Indianapolis, Indiana 46204	13. Type of Report and Period Covered: Interim Report, Nov. 71-May 74
	14. Sponsoring Agency Code: CA 397

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Research Study titled "Soil Stabilization for Erosion Control".

16. Abstract

The potential utility of small percentages of hydrated lime or of Portland cement in stabilizing construction sites against rainfall erosion is under investigation. A laboratory rainfall simulator has been designed and constructed to provide a reproducible "design storm" (3.25 in. per hour intensity, applied for 1 hour on each of two successive days).

Under the test conditions unstabilized (but compacted) Crosby soil eroded to the equivalent of about 90 tons/acre. Treatment with 2.5 percent cement virtually eliminated soil loss; the same level of treatment with hydrated lime reduced it to the equivalent of about 3 tons/ acre, but a curing time of several weeks was required. Even smaller percentages, down to 1 percent, resulted in significantly reduced erosion. A test stand of Alta fescue grass on the same soil was not as effective as the cement or lime treatments.

Investigations into the fundamentals of the stabilization process were carried out and confirmed that aggregation of at least some of the clay into water-stable, millimeter-sized aggregates and partial chemical reaction within these aggregates were involved.

It appears that incorporation of small quantities of lime or cement into the top 2 or 3 inches of soil on construction sites may constitute the basis for relatively inexpensive but effective protection against soil erosion. Further investigation is underway.

17. Key Words	18. Distribution Statement
Construction Soil Erosion; Hydrated Lime Stabilization; Portland Cement Stabilization	

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	115	

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Interim Report

SOIL STABILIZATION FOR EROSION CONTROL

by

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and

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Research Associates

Joint Highway Research Project

Project No.: C-36-50H

File No.: 6-19-8

Prepared as Part of an Investigation
Conducted by
Joint Highway Research Project
Engineering Experiment Station
Purdue University
in Cooperation with the
Indiana State Highway Commission
and the
U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, Indiana
August 28, 1974

ACKNOWLEDGEMENTS

The authors acknowledge with thanks the assistance of Dr. D. N. Winslow, Mrs. Carolyn Brendel, Mr. George Macha, and Mr. Edmond Leo in various phases of the investigation. Appendix II of Part I, "How to Run an Erosion Test Without Really Trying" was written by Mr. Leo.

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INTRODUCTION

This interim report presents the results of the first portion of a larger research study, this initial portion involving (a) the design, development, and testing of rainfall simulation equipment specifically aimed at facilitating comparisons of the erosion resistance of a large number of soils stabilized in various ways, and (b) preliminary evaluation of the effectiveness of modest percentages of conventional soil stabilizing agents (hydrated lime and Type I Portland cement). In addition, investigations were carried out aimed at characterizing the mechanisms of erosion under the impact of rainfall, and the effects of the stabilizers used on these erosion mechanisms. The design, development, and testing of the rainfall simulation equipment and of the associated sample preparation and test devices is described in Part I of this report. In Part II we describe our experimental results as of November 1973, and our interpretations of these results.

The study is aimed at investigating the possibility of developing inexpensive and expedient methods of stabilizing soil temporarily exposed at highway and other construction sites against erosion due to exposure to rainfall. The methods are considered to be temporary stabilization procedures, useful until the area involved is covered by permanent pavement or other structure or otherwise finished in erosion-resistant configuration. The use of conventional soil stabilizers (lime and cement) in much reduced amounts compared with normal soil stabilization practices appeared to be the most likely way of fulfilling these objectives, although other methods will be studied subsequently.

PART I

DEVELOPMENT OF RAINFALL SIMULATION EQUIPMENT

PART I. DEVELOPMENT OF RAINFALL SIMULATION EQUIPMENT

Design Considerations

Characteristics of rainfall and of simulated rainfall of importance in in erosion research

The characteristics of natural rainfall that most strongly influence its erosivity are intensity, drop size distribution, and drop fall velocity. According to Meyer (1) the characteristics of ideal rainfall simulation equipment should include:

(1) Drop size distributions and fall velocities near those of natural rainfall at comparable intensities.

(2) Intensities in the range of storms that produce medium to high rates of runoff and erosion.

(3) Application areas of sufficient size for satisfactory representation of treatments and of erosion conditions.

(4) Uniformity of intensity and of drop characteristics over the area tested.

(5) Rainfall application nearly continuous throughout the area tested.

(6) Angle of impact not greatly different from vertical for most drops.

(7) Consistent reproducibility of artifical storms.

While it is desirable that simulated rainfall reproduce the important characteristics of natural rainfall reasonably well, practically speaking, complete correspondence is impossible. For example, it is exceedingly difficult to produce rainfall which has anything like the drop

size distribution of natural rainfall; usually only a limited range of sizes or a single size is obtained. In designing rainfall simulators it is usual to sacrifice some of the characteristics mentioned earlier. However, it is usually considered desirable to maintain similitude in some respects, particularly those affecting the erosivity of the resulting rainfall. Parameters commonly cited as being important to the erosivity of rainfall include kinetic energy or kinetic energy per unit of area impacted, and momentum, or momentum per unit of area impacted.

Height limitations in design of present equipment

Spatial limitations in the laboratory available for this project restrict the height of rainfall equipment to about 14 feet. This height is insufficient to enable raindrops of all sizes to reach terminal velocity. Hence, the rainfall equipment has been designed so as to obtain a rainstorm as similar to corresponding natural rainstorms as possible while making allowance for the restricted height of fall.

Selection of similitude parameter and appropriate mean drop size and spacing

It was decided in the design of the rainfall simulator for this study, that kinetic energy per unit area would be used as the primary criterion in terms of similarity to natural rainfall.

The kinetic energy per unit of ground surface applied by a natural rainstorm is a function of the rainfall intensity (2). Wischmeier and Smith (3) obtained the following statistical relationship for natural storms:

$$(K.E.)_n = 916 + 331 \log_{10} I \quad \text{.....} \quad (1)$$

where $(K.E.)_n$ is the total kinetic energy in foot-tons per inch of rainfall per acre and I is the rainfall intensity in inches per hour.

The kinetic energy of an artificial rainfall characterized by a single drop size does not depend on the drop size per se, but rather on the velocity which the drops attain; this depends on the height of fall as well as size. This relationship is given by Eq. 2:

$$(K.E.)_s = 3522\ V^2 \quad (2)$$

where $(K.E.)_s$ is the kinetic energy, here expressed in foot tons per inch of rainfall per acre per second and V is the velocity of the raindrops in feet per second.

A relationship between height of fall and drop velocity for various drop sizes was provided by Laws (4). Figure 1 is a plot of drop velocity vs. drop diameter for (a) height of fall large enough for all drops to attain terminal velocity, and (b) the 14 foot height limitation imposed as a constraint on the design of the present equipment.

Calculations employing Equations 1 and 2 and the lower curve of Figure 1 show that a simulated rainfall of single-sized drops falling through 14 feet at a rainfall intensity of 2 inches per hour matches the kinetic energy of a natural rainstorm of this intensity when the drop size is 3.92 mm. However, whether a drop size of this magnitude could be produced in laboratory apparatus capable of delivering a uniform intensity

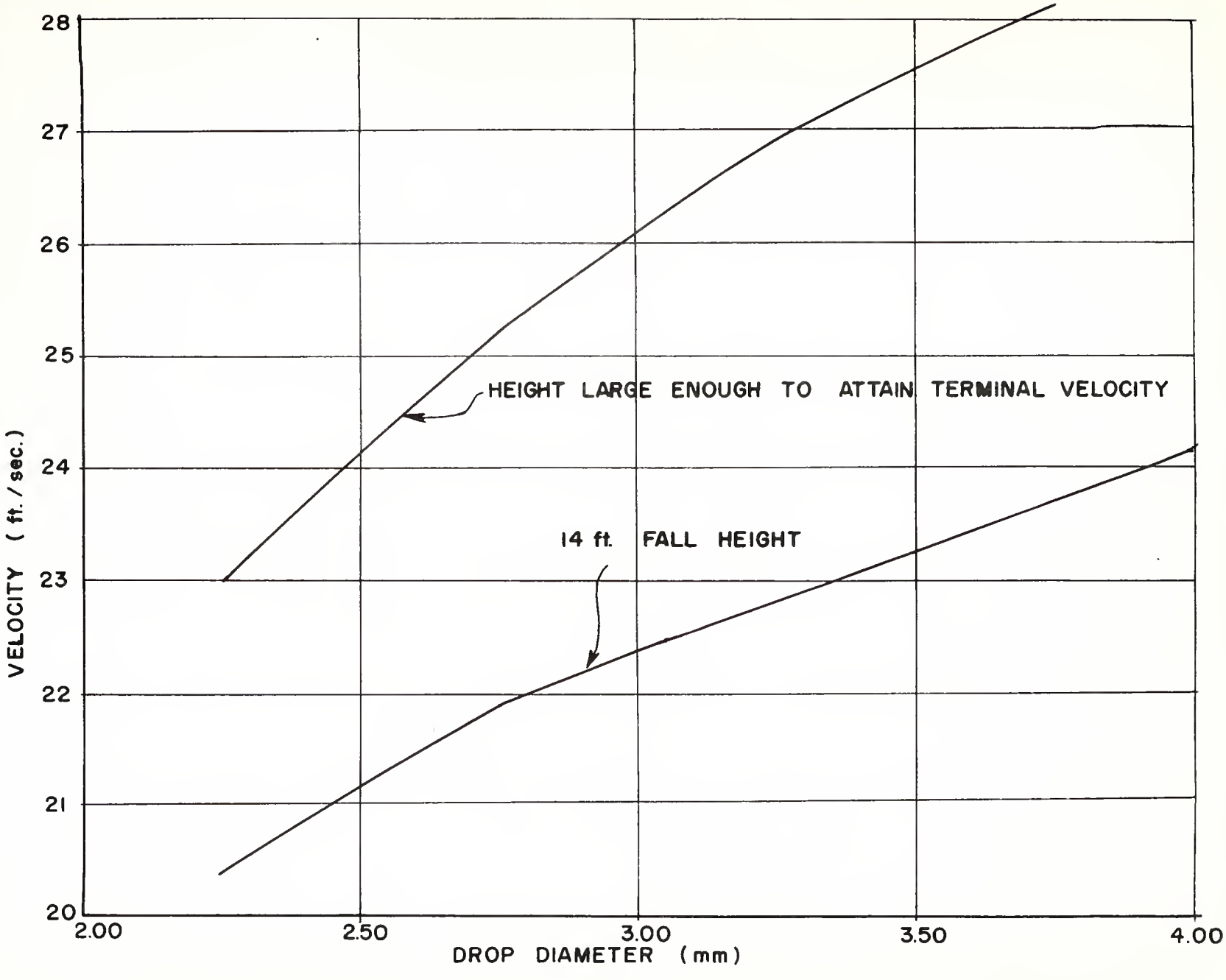


Figure 1. Impact velocity - drop diameter relationships[after Laws, (4)].

of several inches of rainfall per hour was uncertain. If it is impractical, slightly smaller drops might be used to produce at least a reasonable approximation to the desired total kinetic energy. For example, calculations for simulated rainstorms with drop sizes of 3.5 mm and 3.2 mm respectively, under the constrains listed above, yield kinetic energy values of 94.5 percent and 89.6 percent, respectively, of that of a natural 2 inch-per-hour storm.

As rainfall intensity increases the relative kinetic energy delivered by artificial storms of small drop size decreases as well. Table 1 gives the results of calculations relating rainfall intensity per hour, drop size, and corresponding percentages of the kinetic energy of a natural storm of the same intensity delivered by the artificial storm subject to the 14-foot height constraint.

Table 1. RELATIVE KINETIC ENERGY OF SIMULATED RAINFALL

Intensity (in./hr.)	Drop Size (mm.)	Relative Kinetic Energy (percent)
4	3.2	81.8
6	3.2	78.2
4	3.5	84.5
6	3.5	81.8
4	3.9	91.3
6	3.9	87.3

Drop former characteristics

After consideration of a number of alternatives, it was decided to use small-bore stainless steel tubing appropriately spaced in a grid pattern to produce raindrops of the desired range.

The inside diameter of tube required to produce a given drop size can be estimated with satisfactory accuracy from the equilibrium equation relating surface tension force and weight of drop formed:

$$\sigma \pi D = \frac{4}{3} \pi \left(\frac{d}{2} \right)^3 \gamma \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where σ is surface tension in dynes/cm, D is tubing diameter in cm, d is drop diameter in cm, and γ is the density of water in g/cm^3. The calculations indicate that tubes of inside diameters of 0.029 inch, 0.038 inch, and 0.052 inch respectively, will generate drops of the 3.2 mm, 3.5 mm and 3.9 mm diameters previously considered.

In addition to having the proper diameter, it is important that the drop formers be spaced so as to obtain an effectively uniform distribution of drops over the plot to be exposed to rainfall.

The spread of raindrop impact points around the point on the soil surface directly under a tubular drop former was investigated in detail by Mutchler (5), who showed experimentally that the impact points were distributed normally around the geometric center. The distributions were characterized by geometric standard deviations of the order of 1 cm, indicating that about two-thirds of the drops would fall within a circle of this radius. Actual values of the standard deviation varied

slightly with drop size, being 1.05 cm for 3.5 mm drops, the smallest tested, and 1.32 cm for 5.6 mm drops, the largest tested.

Mutchler calculated distribution statistics that would result from drop formers spaced in a triangular pattern such as would be suitable for the design of simulated rainfall devices. For example, when drop formers are placed 3 standard deviations apart, the coefficient of variation of the resulting drop impact distribution is 13.4 percent. Under this condition, the corresponding local intensity at the impact point just under the drop formers is 130 percent, and that at the minimum intensity point half-way between centers is 84 percent of the overall average intensity, respectively. Mutchler considered that a spacing of about 3.5 standard deviations, giving a coefficient of variation of approximately 30 percent and a range from points of maximum and minimum intensities of 167 percent to 67 percent of the average value, would be acceptable for simulated rainfall devices used in soil erosion studies.

Results of Preliminary Design Tests

A series of preliminary design tests were carried out to evaluate the effect of various sizes of drop formers and a method of varying intensity of rainfall.

Preliminary experimental water applicator boxes were constructed using stainless steel drop formers of four different internal diameters ranging from 0.0195 inch to 0.041 inch. The drop formers were spaced in the triangular pattern recommended by Mutchler (5) at a fixed spacing of 1.0 inch (2.54 cm).

Runs to evaluate the size of the drops produced under fixed water pressure heads of 10, 20, 30, and 40 mm maintained above the drop formers were carried out. The drop size was determined by collecting 25 drops in a container and measuring the resulting volume, the drops being considered to be spheres of volume of 1/25th of the total volume collected. The drop size data are given in Table 2.

Table 2. Drop Size as a Function of Inside Diameter of Drop Former and of Water Head.

Inside Diameter of Drop Former (in.)	Head of Water (mm.)	Drop Diameter (mm.)
0.0195	20	3.08
	30	3.08
	40	3.08
0.023	20	3.18
	30	3.18
	40	3.18
0.027	10	3.34
	20	3.34
	30	3.30
	40	3.30
0.041	10	3.84
	20	3.92
	30	4.16

All of the tests were carried out at 21 $\pm$ 0.5° C.

It is clear from the results of Table 2 that drop size is relatively independent of water head, at least in the smaller size ranges, and that the size is primarily controlled by the drop formers and quite repeatable.

Tests to determine the rainfall intensity produced under various pressure heads were carried out using the three smallest drop formers previously mentioned. These were conducted over 1-hour periods and led to the data plotted in Figure 2. They indicate that the minimum rainfall intensity that can be produced by this preliminary apparatus is about 5 inches per hour, which is an unreasonably high value for present purposes. The intensity could be reduced by spacing the drop formers more widely, or by regulating the flow through the drop formers by another means; smaller water heads seemed to be impractical in terms of reproductibility. After some experimentation it was found that a needle valve inserted in the water supply line could effectively regulate the intensity of rainfall at reasonably low values when used with the smallest inside diameter tubings. Results of experiments checking this point are given in Figure 3, in which rainfall intensity is plotted against needle valve settings (i.e., number of revolutions of the valve stem) for the 0.0195 inch diameter drop formers.

The three upper points on the plot were runs carried out under a nominal head of 30 mm; the lower point under a head of 40 mm. It appears that with this arrangement for delivery of water the rainfall intensity achieved is relatively independent of the head and is effectively controlled by the needle valve setting.

The minimum effective rainfall intensity for this arrangement seems to be about 3.5 inches per hour. Further reduction can be secured by reducing the number of drop formers per unit area, i.e., by increasing their spacing. The theoretical effect on rainfall intensity of increasing the spacing from 1.0 inch to 1.2 inch and to 1.3 inch was calculated for

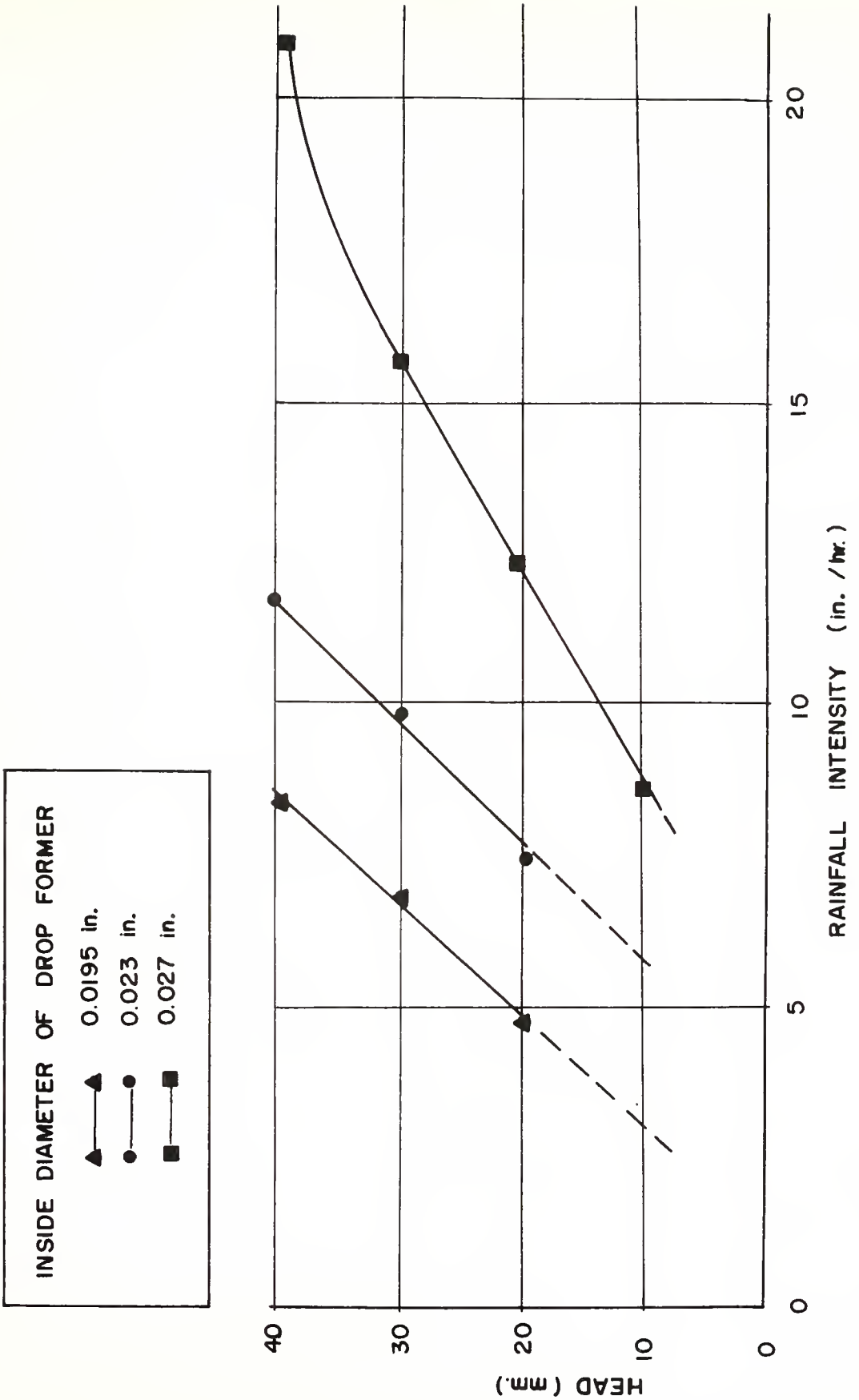


Figure 2. Intensity of rainfall as a function of size of drop former and of water head maintained.

the different needle valve settings and these values are also plotted in Figure 3. It appeared that an increase in spacings to 1.3 inches could be used to effect a rainfall intensity reduction to as little as 2 inches per hour.

The effect of such increases in spacing of the drop formers on the resulting areal uniformity of the rainfall was estimated from the data of Mutchler (5). Mutchler's data indicates a standard deviation (σ) of 1.08 cm is characteristic of 3.5 mm drops. For such a drop a 1.3 inch spacing corresponds to 3.06 σ while a 1.2 in. spacing corresponds to 2.80 σ . As discussed previously a 3 σ spacing generates a distribution such that the wettest spot receives 130 percent of the mean amount of water and the driest spot 84 percent of the mean. The corresponding data for the 1.2 inch spacing are 119 percent and 90 percent.

In the present experiments the use of a 3.08 mm drop size as is obtained from 0.0195 inch drop formers is contemplated, rather than a 3.5 mm. drop size which was the smallest investigated by Mutchler. This should decrease the standard deviation slightly. Further, and perhaps more important, the limited height of fall (14 feet) should reduce the dispersion around the drop former center by some additional unknown factor. Nevertheless, the judgement was made that use of a 1.2 inch spacing in a triangular array would produce rainstorms of sufficient uniformity to be clearly acceptable for comparative soil erosion studies.

A rainfall applicator was then constructed using 0.0195 inch diameter drop formers, producing drops of 3.08 mm diameter, and spaced 1.2 inches apart in a triangular array. A plan view of this applicator is given as Figure 4.

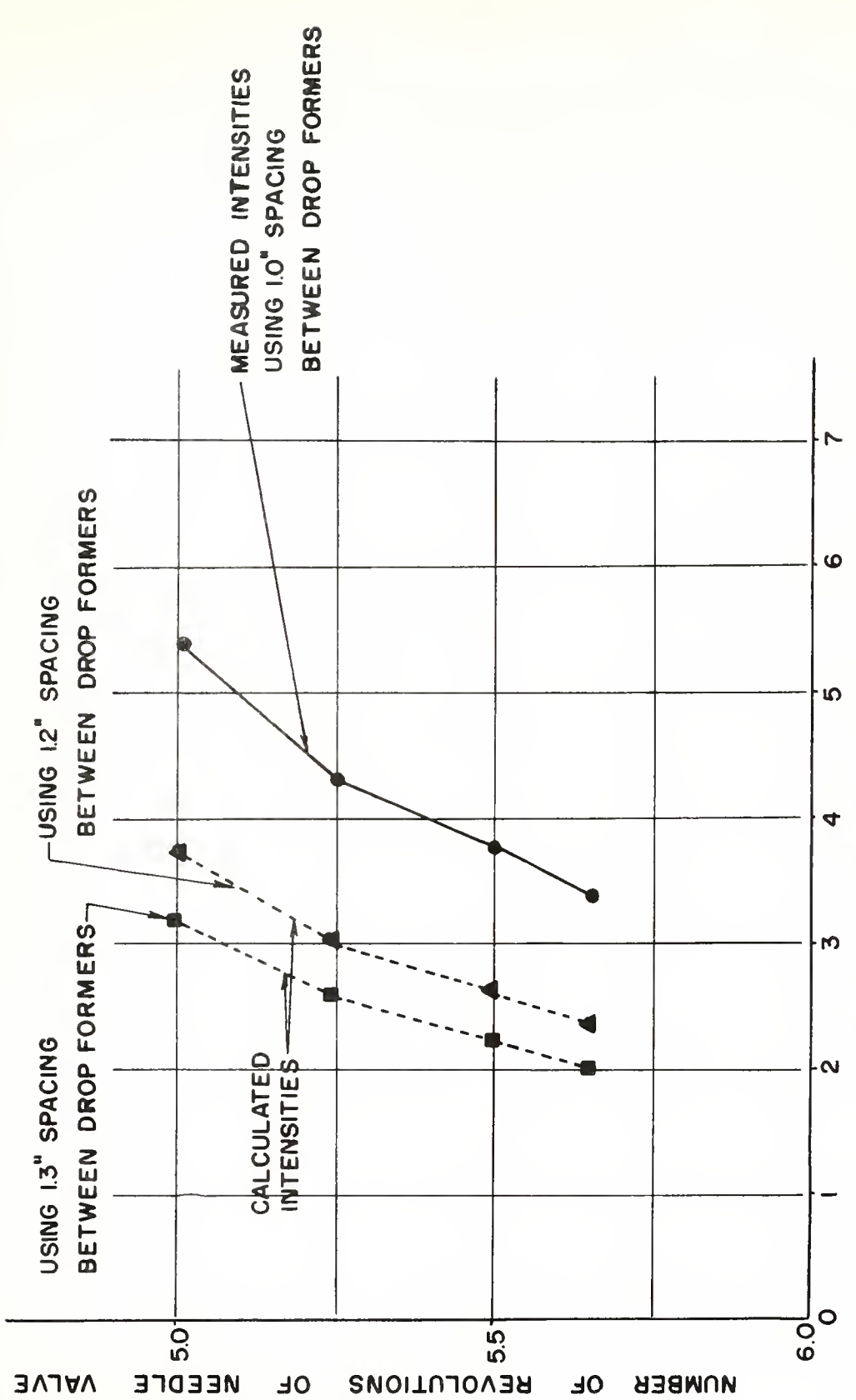


Figure 3. Intensity of rainfall as a function of needle valve control setting (number of revolutions).

Calculations of the relative kinetic energy per unit area of artificial rainstorms produced by this device compared to those of natural rainstorms of the same intensities were made, and the results given in Table 3.

Table 3. Kinetic Energy of Simulated Rainstorms Using 3.08 mm. Drops and 14 Feet Fall, Relative to Those of Natural Storms of the Same Intensities.

Rainfall Intensity (in. per hour)	Relative Kinetic Energy (percent)
2	88.0
4	80.1
6	76.1

The data indicate that the proposed simulated rainstorms provide reasonable approximations to the kinetic energies of natural storms of the same intensities.

Description of Simulated Rainfall Equipment Developed

The final rainfall simulation equipment developed in this project and the associated soil erosion specimen holders are shown in Figure 5. The following major sub-assemblies are indicated:

1. Shut-off valve for rapid fill system (line I).
2. Flow control needle valve, for controlling intensity of rainfall during test. (line II)
3. Bleed valve for removal of trapped air from rainfall applicator box.

4. Constant head tank.
5. Water storage tank (three separate units provided)
6. Secondary water line filter.
7. Primary water line filter.
8. Main water supply shut-off valve.
9. Water pump.
10. Valve for controlling discharge from main storage tank (5) to constant head tank (5).
11. Rainfall applicator assembly.
12. Specimen container assembly.

The applicator box assembly (11) consists of a 24 inch x 24 inch plexiglass sheet set in a 1 inch well, into which 407 drop formers of inside diameter 0.0195 inch have been positioned in a triangular array. The spacing between drop formers is 1.2 inches. Each drop former projects 0.2 inches below the plexiglass sheet, and the drop formers have been sealed in position using Armstrong refrigerator cement. Figure 4 shows a plan view sketch of the applicator assembly.

The water flow control system consists of the items numbered (1) through (10) in the previous list. Water is let in through the main water supply shut off valve (8), is filtered by the primary filter 7, and is passed to the main storage tank, (5). Three separate storage tanks are provided; water is stored for several days so as to attain temperature equilibrium prior to the start of a test.

Water from one of the main storage tanks (5) is pumped by the pump (9) through the secondary filter (6) to the constant head tank (4), and through lines I and II to fill the reservoir of the rainfall

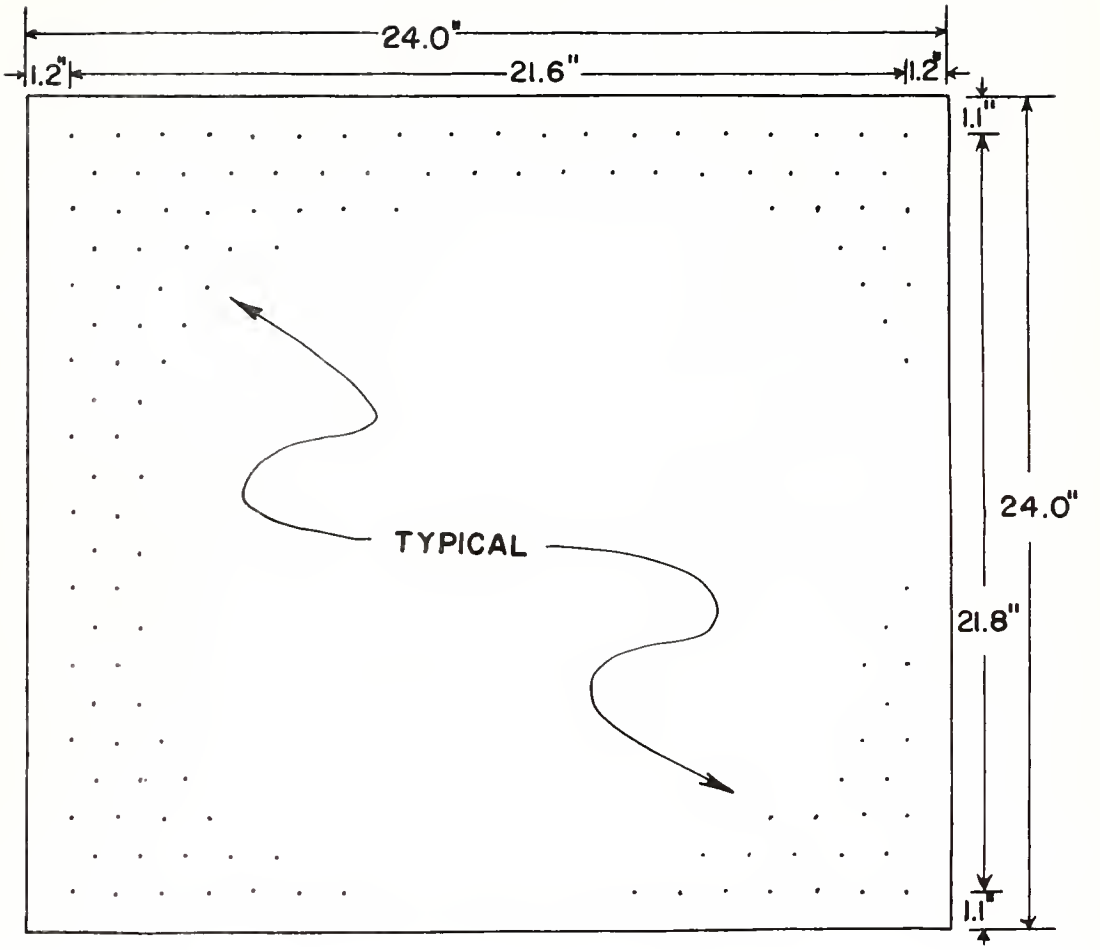


Figure 4. Spacing pattern of drop formers in rainfall applicator assembly.

applicator. When this is filled the shut off valve (1) is closed and additional water is delivered to the rainfall applicator only through line II, the rate of flow being controlled by the setting of the flow control needle valve (2). The water head is regulated by the position of the outside cylinder of the constant head tank, which is positioned with the aid of friction on the main O-ring, and may be moved up or down as desired.

The bleed valve (3) serves for the removal of air trapped in the reservoir of the rainfall applicator.

The rate of drop formation, i.e., rainfall intensity, is controlled primarily by the setting of the needle valve (2), and also to some slight extent by the water pressure head, as determined by the positioning of the constant head tank outer cylinder. The flow of water reaching the constant head tank is regulated by shut off valve (10); extra water overflows from the constand head tank (4) and returns to the storage tank (5).

Appendix I provides a summary of the operating instructions and precautions observed in the routine use of the rainfall simulation device, and Appendix II provides a complete and detailed informal manual for its operation.

Description of Erosion Test Devices Developed

Soil specimen holders and supports

Generally speaking, soil erosion is usually recognized as comprising the results of processes of detachment and transportation of soil materials by an erosion agent, as has been defined by many authors. The problem can thus logically be broken down into two separate parts, soil detachment and soil transportation.

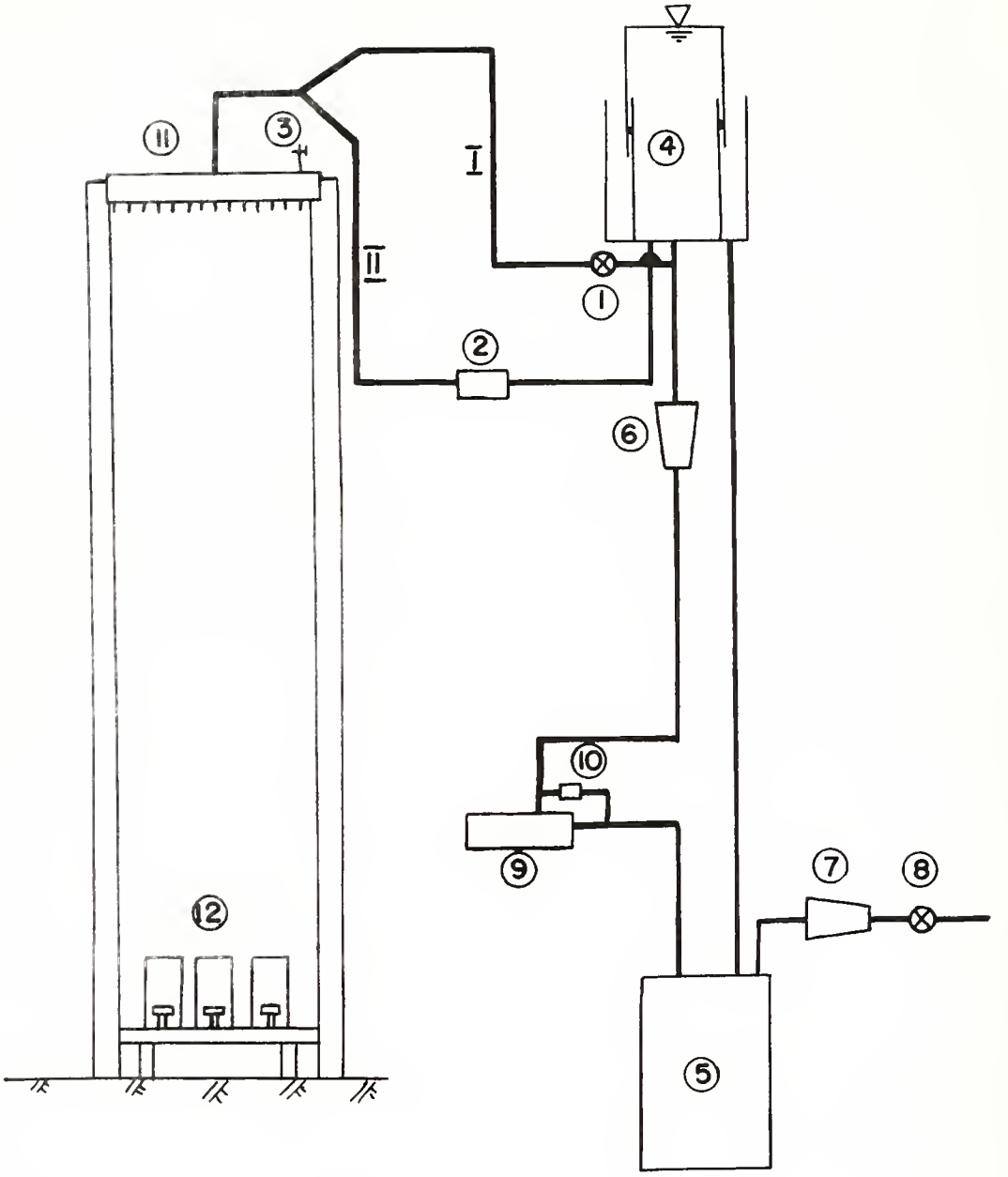


Figure 5. Flow control system for rainfall simulator assembly.

The present erosion test equipment was designed and fabricated in order to investigate the first of these phases, soil detachment under the impact of water drops. This is the primary concern in evaluating the effectiveness of soil stabilization treatments for erosion control for construction sites. The diameter of the soil containers was chosen to be small enough that the specimens would be free of the effects of soil transportation. The 4-inch specimen diameter adopted clearly satisfies such a requirement; splashed particles have been shown to move horizontally as much as 5 feet on level surfaces.

The specimen depth has been standardized at 1 inch since presumably the successful soil erosion stabilization treatments of interest would suffer comparatively little erosion.

These dimensions are not unreasonable when compared with those normally encountered in soil erosion research, splash cups of 3-1/2 inch diameter and 2-inch depth having been commonly used for this purpose (6, 7).

The specimen holders designed for the present investigation consist of a ring, a base, and a support. The position of the base relative to that of the support can be adjusted at will, since it is retained in place by friction on an O-ring. Since the movable base system can be used in such a way as to eliminate the effect on soil erosion of progressive lowering of the eroding specimen surface into the interior of a container, no calibration or correction for "splash cup effect" (8) is required. The specimen is extruded out of the holder to an appropriate extent after the first hour of the rainfall cycle.

The support is so arranged that the specimen surface is tilted 5° from the horizontal. This design feature assists in providing free drainage from the surface and prevents the accumulation of water on the surface. Free water resident on the eroding surface would strongly influence the apparent detachability of soil particles by absorbing the raindrop impact, and this must be avoided for a proper evaluation.

Preparation of soil specimens

Stabilized soil test specimens of appropriate dimensions (4 inches in diameter and 1 inch in height) are produced using metal molds specially fabricated for this study. The appropriate soil-stabilizer mixture is compacted in the device using a standard Proctor compaction hammer. The desired unit weight is obtained by adjusting the number of blows so that the total energy applied to the system per unit volume is the same as that of the standard Proctor compaction test, which is normally made on a much larger volume of soil. Compactive efforts less than that equivalent to the standard Proctor compaction tests are also possible and have been employed.

The compacted specimens are retained in the mold during the curing process. The curing procedure used involves sealing the specimen and mold in a plastic sack and curing for the desired time in a fog room in which the temperature is maintained at 74°F. After the desired curing period the specimens are removed from their molds and carefully positioned in place in the sample holder. Details of this portion of the apparatus are given in Figure 6a.

System for recovery and measurement of eroded soil

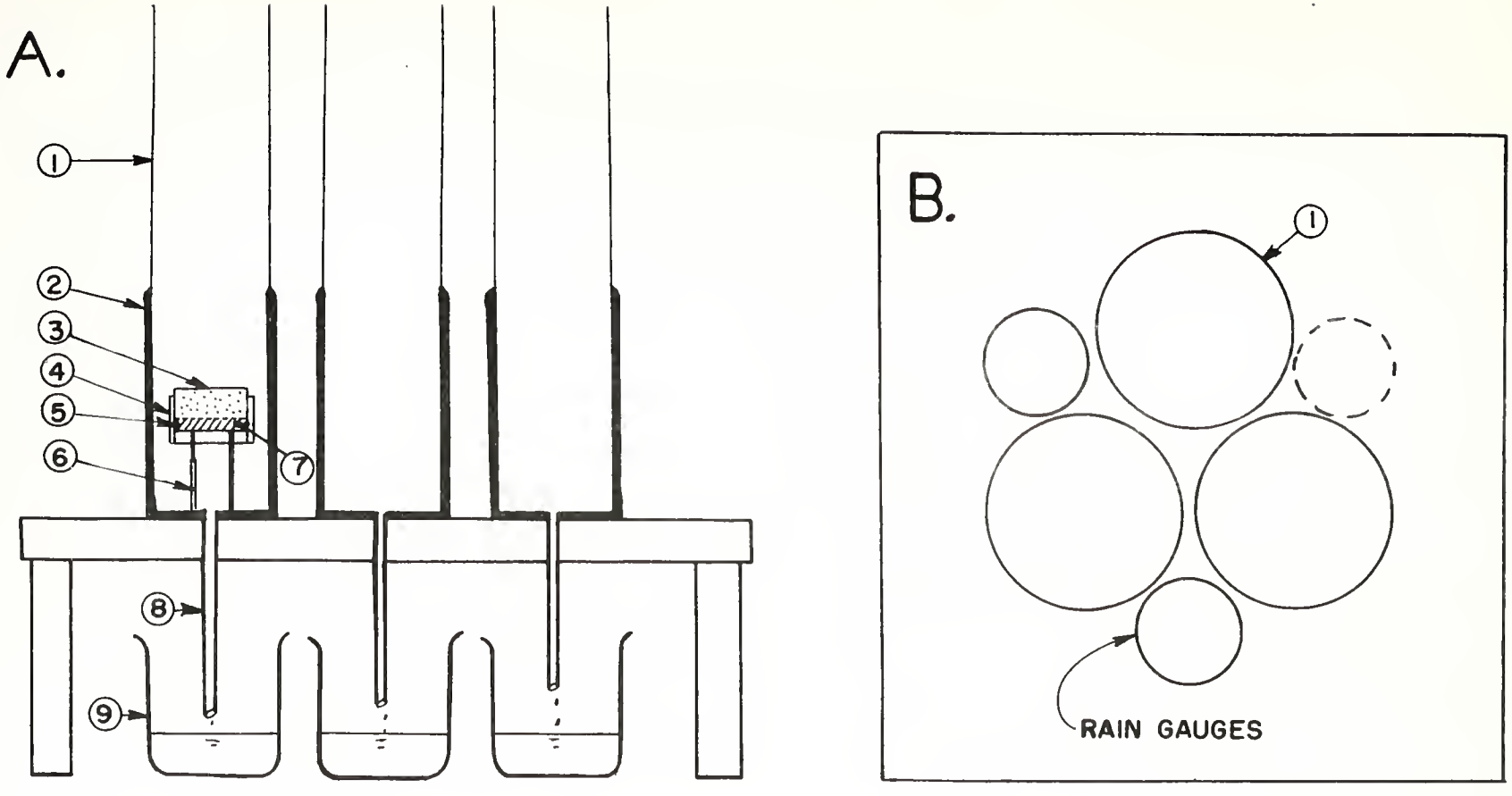
A system has been provided for the purpose of recovering the eroded soil lost by each specimen and thus evaluating the erosion that has taken place. The specimen holder system and the system provided for the recovery of eroded soil are diagrammed in Figure 6a.

As indicated in Figure 6a facilities are provided for handling three replicate specimens and the associated apparatus for each. Each specimen and mounting assembly is enclosed in a large metal cylinder of 6 inches in diameter and 12.5 inches in height (3); these rest on a supporting bench. The specimens are held approximately half-way up the cylinder. Run-off water and eroded soil are swept to the bottom of the cylinder and pass through a hole into a tube which delivers the soil-water suspension to a large beaker positioned underneath the supporting bench. At the conclusion of a rainstorm the collection beakers are removed, the soil particles are allowed to settle overnight, and the clear supernatant water is decanted. The soil removed is oven dried at 105° C and the mass of soil eroded is thus determined.

Rainfall intensity check system

In operation, the three replicate cylinders containing the soil specimens are positioned in a triangular array as indicated in Figure 6b. Positions are provided for 4-inch rain gauge cylinders to be accommodated between the specimen container cylinders as indicated in the figure. An accurate record of the rainfall intensity actually delivered in each rainstorm is thus provided.

An overall calibration of the rainfall intensity delivered by the system as finally evolved was carried out using rain gauges



1. EXTENSION WALL
2. SAMPLE CONTAINER
3. SPECIMEN
4. OUTSIDE CYLINDER OF SPECIMEN HOLDER
5. "O" RING
6. SUPPORT
7. BASE OF SPECIMEN HOLDER
8. TYGON TUBE
9. BEAKER

Figure 6. (A) Specimen mount assembly and system for recovery of eroded soil.
(B) Positioning of test devices and rain gauges: plan view.

positioned in the spots normally occupied by the specimen cylinders. The results are given in Figure 7 in which measured rainfall intensity is plotted as a function of the positioning of the flow control needle valve. Intensity delivered proved to be an almost linear function of needle valve control setting (in revolutions from the closed position) at least over the setting range appropriate to the investigation.

Standardization and calibration of rainstorm pattern

It was finally decided, in conformity to established custom in soil erosion testing, that the "standard test storm" would consist of a two-part sequence: one half of the applied rainfall delivered on each of two successive days with a 24-hour period between the two portions.

The design storm" desired consists of a total of 6.5 inches of rainfall applied at the rate of 3.25 inches per hour on the two successive days. The actual measured intensities are normally between 3.1 and 3.4 inches per hour. Since the purpose is to evaluate the comparative resistance to erosion of stabilized, rather than natural soils, the slight variation in intensity was felt to be not a serious difficulty.

The results of a series of three tests, each carried out in triplicate, are given in Table 4 to provide an indication of the performance of the equipment and of the repeatability of the measurement of soil erosion.

The soil used was an illite-bearing commercial clay ("grundite") not stabilized, but simply compacted at optimum moisture content (20% M.C.) using the energy equivalent of standard Proctor compaction. The measured intensities of rainfall were 3.26, 3.14, and 3.15 inches per hour, respectively, and the average value of soil lost per cm^2 of exposed surface

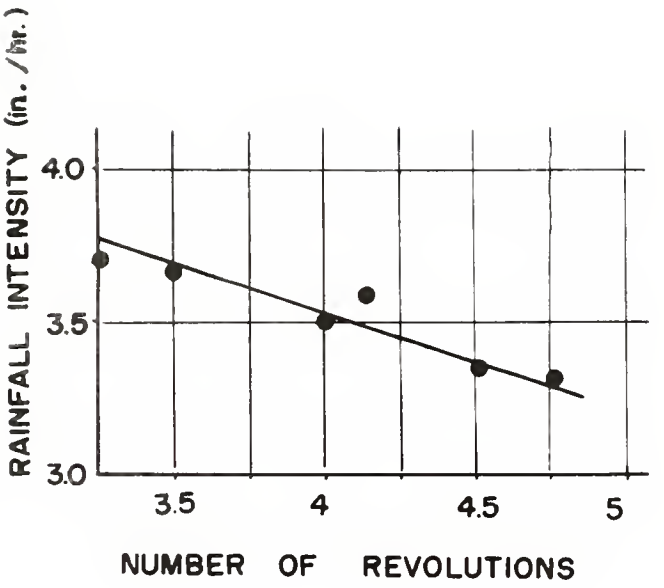


Figure 7. Rainfall intensity actually delivered as a function of needle valve control setting (number of revolutions).

was 1.72 g. with a standard deviation of 0.12 g/cm^2. These data lead to a coefficient of variation of 6.9 percent, indicative of a well-controlled testing situation. Thus the variability of the soil erosion test procedure seems to be entirely adequate for distinguishing between effective and ineffective soil stabilization treatments.

Table 4 - Calibration Trials of Soil Erosion System[1]

Rainstorm Series	Specimen No.	Soil Dry Unit Wt. (g/cm^3)	Measured Rainfall Intensity (in/hr.)	Soil Eroded (g/cm^2 of Exposed Surface)	Average (g/cm^2 of Exposed Surface)
I	1	1.53	3.26	1.72	
	2	1.53	3.26	1.64	
	3	1.50	3.26	1.64	1.67
II	4	1.52	3.14	1.68	
	5	1.53	3.14	1.74	
	6	1.52	3.14	2.00	1.81
III	7	1.57	3.15	1.67	
	8	1.57	3.15	1.58	
	9	1.57	3.15	1.82	1.69

Soil Erosion Loss Statistics:

Mean = 1.72 g/cm^2 of exposed surface

Standard Deviation = 0.12 g/cm^2 of exposed surface

Coefficient of Variation = 6.9 percent

[1] Each rainstorm series consists of 3 replicate specimens exposed to one hour of rainfall on each of two successive days. The soil was grundite, compacted at an effort equivalent to that of the standard Proctor compaction test, but not otherwise stabilized.

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(3) Wischmeier, W. H. and Smith, D. D., "Rainfall Energy and its Relationship to Soil Loss," Trans. Amer. Geophysical Union, Vol. 39, pp. 285-291, 1958.

(4) Laws, J. O., "Measurements of Fall Velocity of Water Drops and Rain Drops," Trans. Amer. Geophysical Union, Vol. 22, pp. 709-721, 1941.

(5) Mutchler, C. K., "Using the Drift of Water Drops During Fall for Rainfall Simulator Design," J. Geophysical Res., Vol. 70, No. 16, pp. 3899-3902, 1965.

(6) Woodburn, R. A., "The Effect of Structural Condition on Soil Detachment by Raindrop Action," Ag. Engineering, Vol. 29, pp. 154-156, 1948.

(7) Bisal, A. F., "Calibration of Splash Cup for Soil Erosion Studies," Ag. Engineering, Vol. 31, pp. 621-622, 1950.

APPENDIX 1

Summary of Operating Instructions and Precautions

1. Turn on the water pump switch to pump water to the constant head tank. It is desirable to cycle water for several tens of minutes if water in the constant head tank has been exposed to dust or dirt. The air bleed valve (3) should be open.

2. The applicator box is filled with water through tygon tubing lines I and II (see Figure 4); i.e., both shut-off valve (k) and needle valve (2) should be completely open and the outside cylinder of the constant head tank (4) should be positioned at its uppermost position.

3. As the applicator box becomes almost filled, head level should be reduced by lowering the outside cylinder of the constant head tank to its prescribed test position.

4. The air bleed valve should be closed as soon as the applicator box is full of water. Immediately after that, the needle valve (2) should be closed. Careful attention must be paid to avoid building up high pressure in the applicator box, which can cause leakage. Also, it is very difficult to drive out all of the air trapped in the applicator box, a little being trapped along the edges regardless of efforts to remove it. However, small amounts of trapped air proved to have little effect on the rainfall generated by the apparatus, and may be ignored.

5. The needle valve (2) should next be adjusted so as to give the desired rainfall intensity.

6. During the rainstorm, attention should be given to the drop formers; occasionally some of these become plugged and stop producing water drops. Often they may be freed and resume functioning after simply being touched at the end with a finger; other malfunctioning drop formers seem to become clogged with calcium compounds precipitated from the water, and these can be cleared by inserting a needle into the bore of the tube. It is possible, and important to prevent these bore-clogging problems by blowing out all vestiges of water after the test, as indicated in the next item.

7. After completion of a rainfall test, all of the water should be removed from the applicator box by connecting the air bleed line (3) to a compressed air line and blowing out all residual water through the drop former tubings. After this, any residual water trapped in any of the drop formers should be removed by blowing compressed air through those tubings from the bottom end.

8. Occasionally leakage around drop former tubings occurs and interfers with drop production. Leaks around tubings can be sealed by applying a silicone-type glue with a fine brush around each affected tubing. The surface around the tubings needs to be dried in advance. About one day of curing is required for the leaks to seal properly.

9. It is quite important that the drop formers produce drops all at the same relative rate; failure to do this will produce a non-uniform drop distribution on the specimens. This should be checked by visual observation at frequent intervals.

APPENDIX II

How To Run An Erosion Test Without Really Trying

A. Sample Preparation

1. Remove desired samples for testing from the humidity room located in the basement.

2. Record the mold number. Reweigh the mold with the compacted soil. Record both numbers in appropiate locations on data sheet. (See enclosed typical data sheet)

3. Disassemble specimen holders and apply a thin coating of silicone lubricant to the inside of the holders. Reassemble holders. (See Fig. 1)

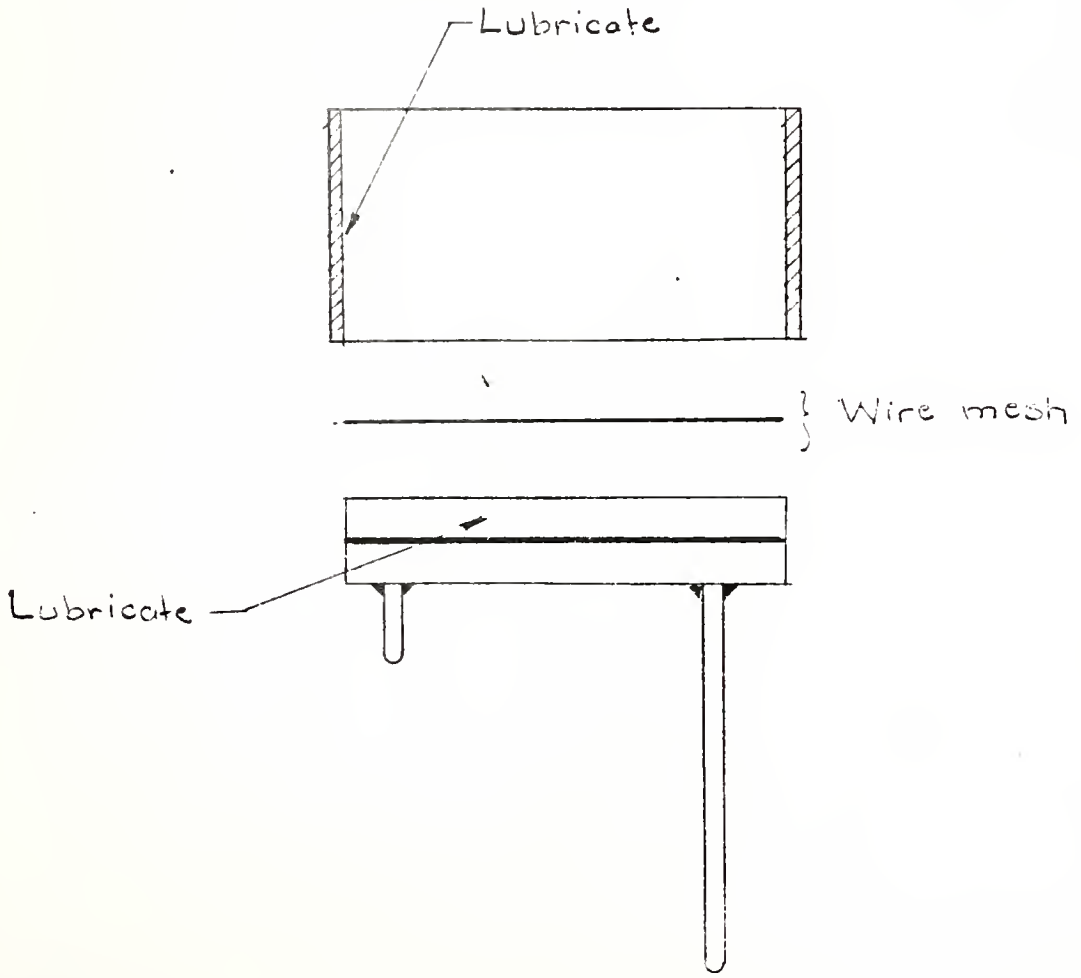


Fig. 1 Exploded View of Specimen Holder

4. Holders are numbered 1, 2, & 3. If soil specimens are numbered 120, 121, 122, Specimen 120 goes to holder #1, Specimen 121 goes to holder #2, etc.

5. Carefully remove compacted soil sample from the mold and place side facing up towards you face down into the assembled holder. Carefully push sample down into holder until ≈ 1/4" of sample is projecting from the holder (See Fig. 2)

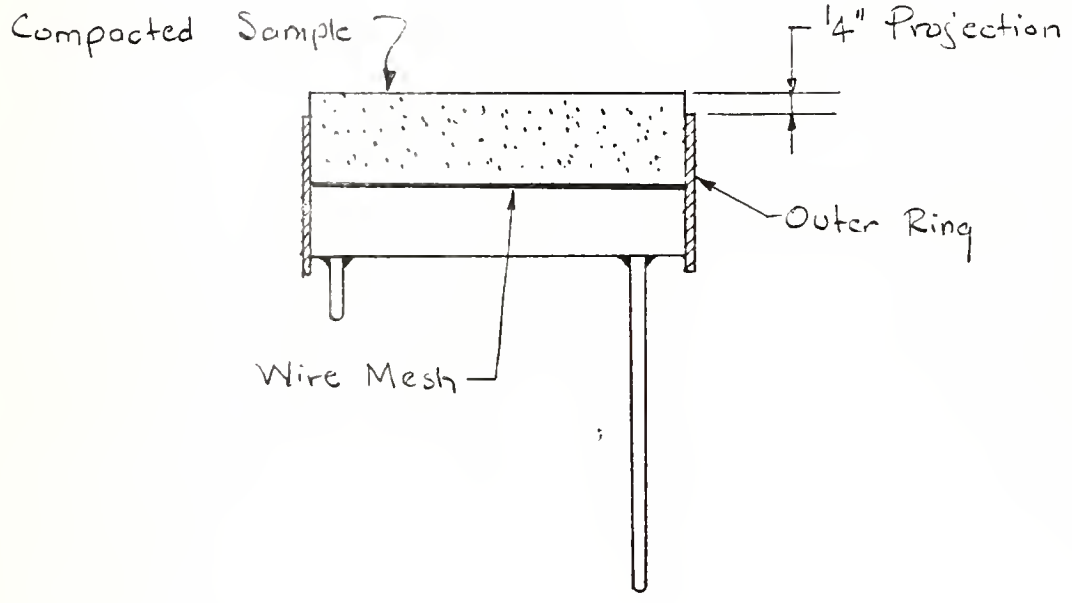


Fig. 2

6. Repeat Step 5 for the remaining two specimens.

7. Attach plastic tubing to the 3 cylindrical containers and place into holes provided in the plexiglass base (See Fig. 3)

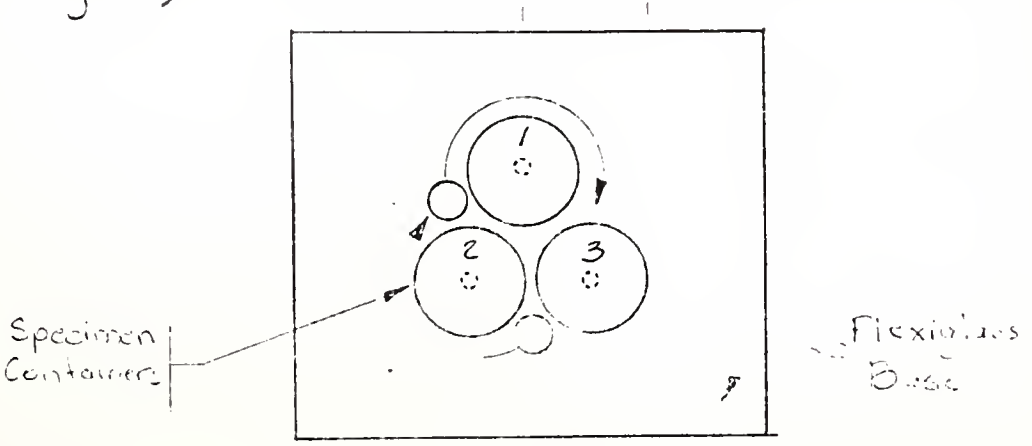


Fig. 3

8. Carefully place sample holder into container making sure handling does not damage edges of sample. Make sure the guide on the sample holder match the guide in the container. Rotate the container to see that there is a positive contact. If there is wobbling of the specimen, refit the two guides until there is no wobbling under rotation (See Fig. 4)

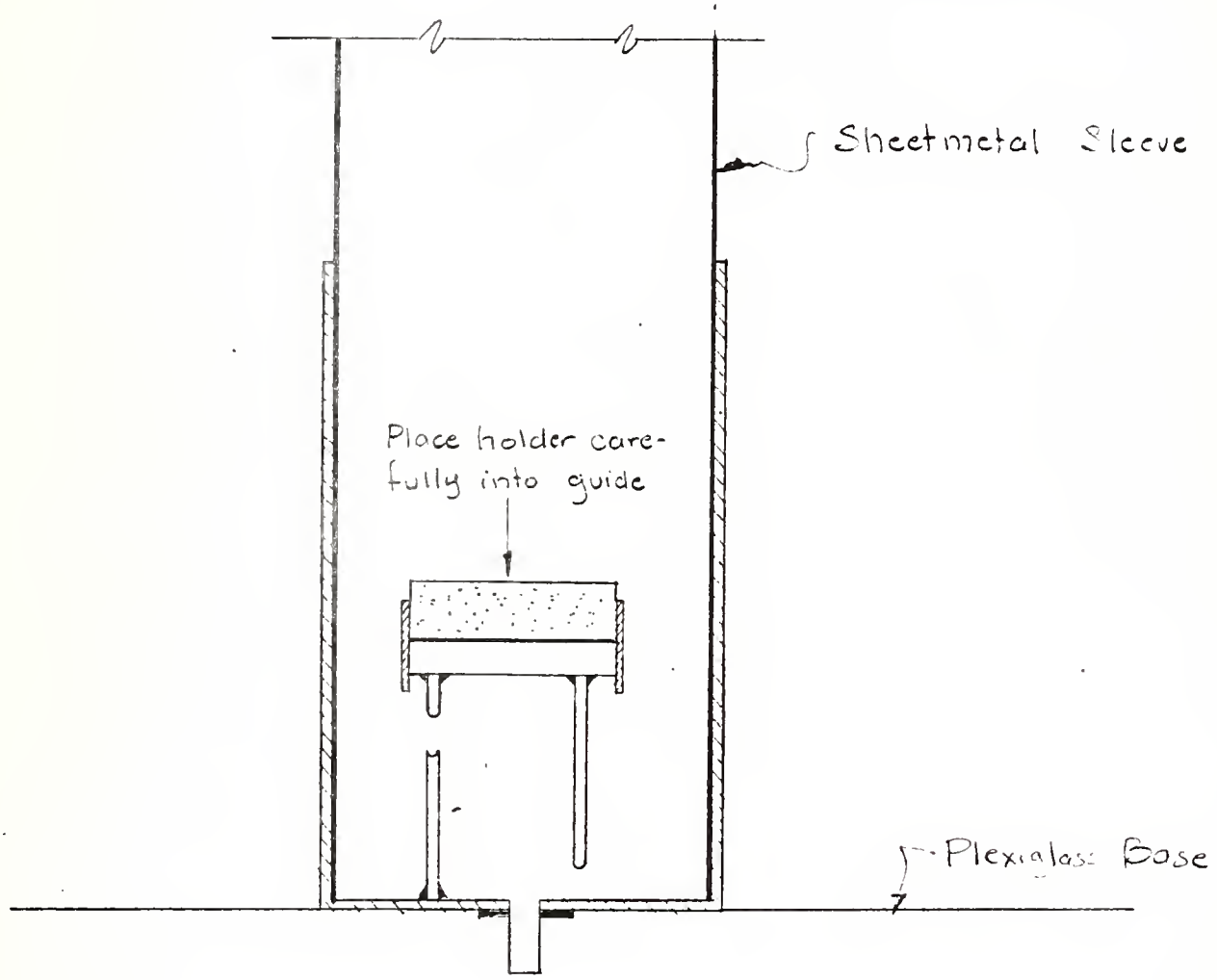


Fig. 4

9. After all three specimens have been put into place, insert the sheet metal sleeves into the containers and place the plastic covers on the sleeves. Place the appropriately numbered beaker under each container to catch the eroded soil.

B. Running The Test (Test runs 1 hour)

1. Remove the wooden cover from the desired barrel. Record the temperature of the water in the barrel from the thermometer hanging along the side of the barrel.

2. Connect the pump and switch on.

3. Climb up to the top of the structure and open Valves #1 & #2 FULLY. When valve #2 has been fully opened, close it back slightly until indicator is opposite position 1 on numbered circle. As plexiglass box is filling make sure there are no air bubbles trapped in the water lines. If there are air bubbles present remove them while box is filling. (See Fig. 5)

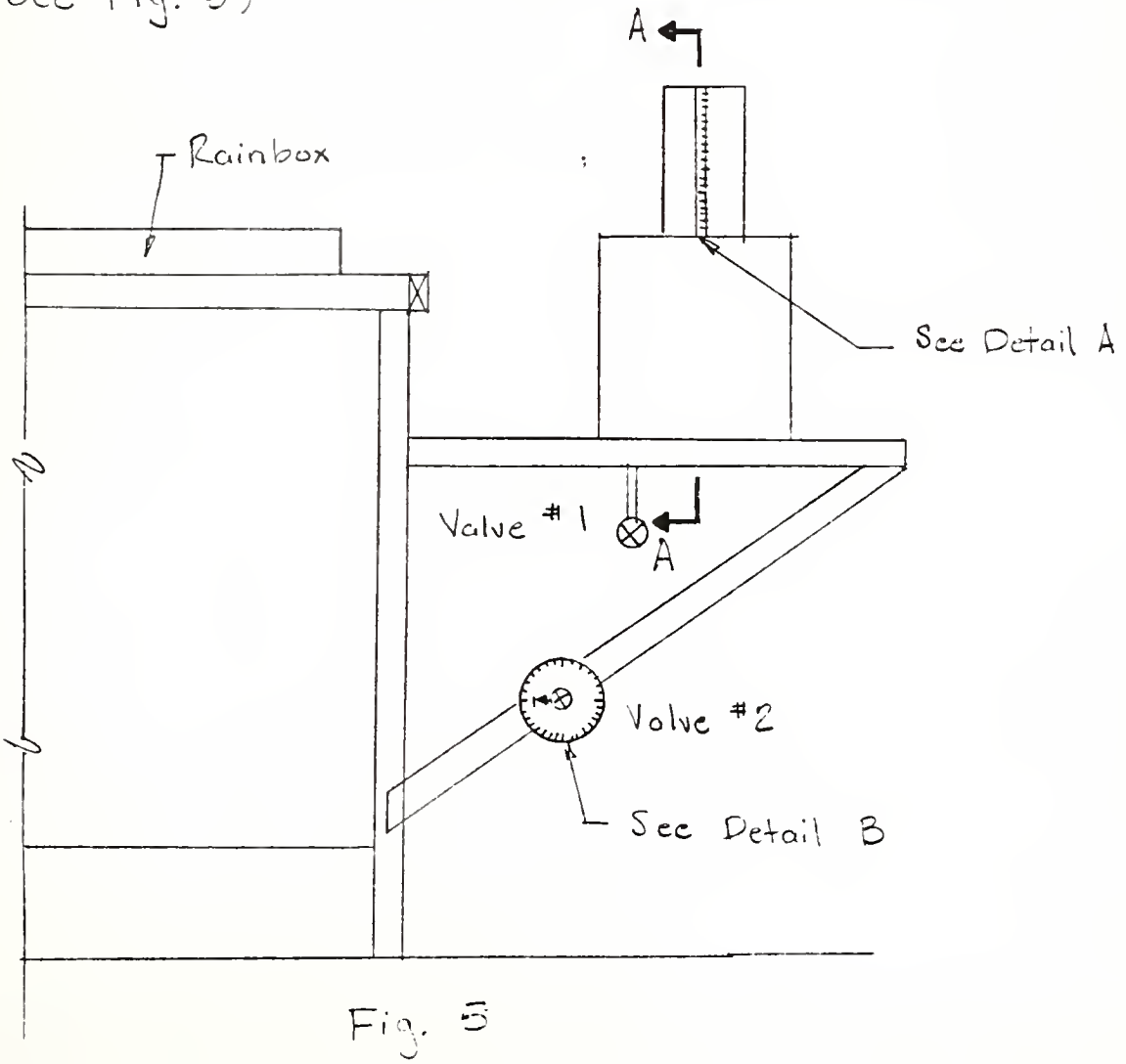
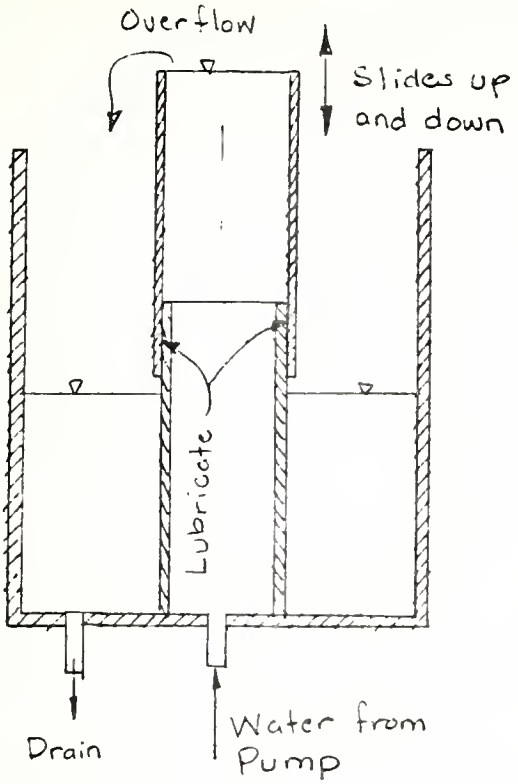
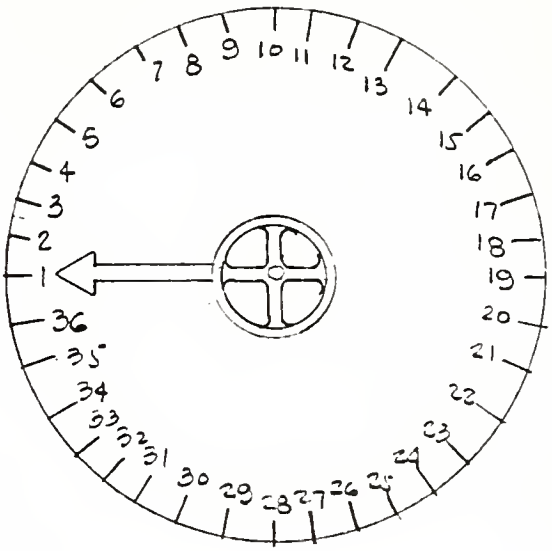


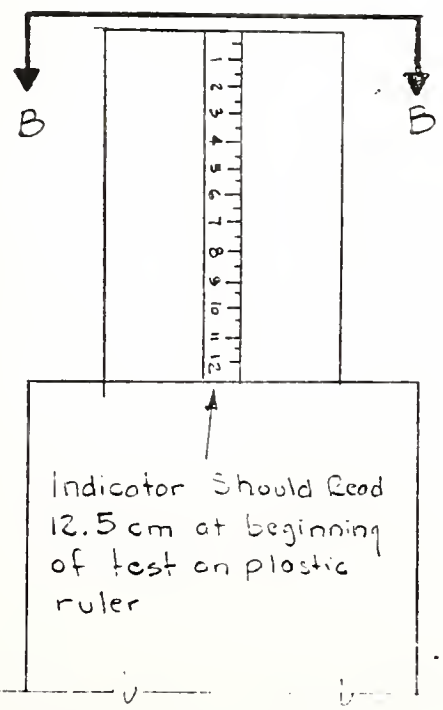
Fig. 5



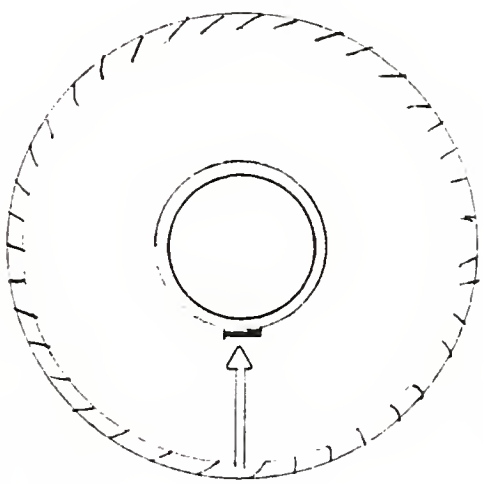
SECTION A-A



DETAIL B



DETAIL A



SECTION B-B

4. Outer cylinder as shown in Section A-A may be raised to a level of 19 cm or more to speed filling of the rain box. Caution: Make sure cylinder is pushed back down to 12.5 cm before beginning of test.

5. As soon as the box is filled, clamp the open plastic tube leading into the box and shut Valve #1 as quickly as possible. After closing valve #1, proceed to close valve #2 counterclockwise 4 revolutions and set pointer on number 1 position. This is the standard for each test.

6. Proceed to inspect all the tubings and clean out as many of the tubings that are clogged with the needles. Make sure as many of the tubings in the central portion of the box are unclogged

7. After satisfying yourself that the tubings are operating effectively, climb back down and start the test at a time convenient to yourself.

8. At the beginning of the test put in the rain gauges into position as shown in Fig. 3 and remove the plastic covers.

9. Every 20 min. shift the position of the rain guages and rotate each container $\times 120°$ so that the sample receives an even rainfall distribution.

10. At end of the test, close valve #2 completely and turn the pump off.

11. Remove the rain guages and replace the plastic covers on the sheet metal sleeves. Record the amount of rainfall with the graduate cylinder behind the machine.

12. Unclamp the tubing and let atmospheric pressure drain the box. When the box refuses to drain under atmospheric pressure, attach the air hose and <u>GENTLY</u> open the air valve so that there is a steady drainage from the box

13. When box is completely drained (≈30 min) remove air hose and use it to clean out the individual tubes.

14. After cleaning replace the metal cover over the cylinder to prevent dust from getting into the water.

15. Refill the water barrel that was used and transfer hoses and thermometer to another barrel.

16. Remove beakers from underneath the plexiglass base and put them inside the machine. Clamp the plastic hoses with the clamps that are provided.

RUN #2

17. Siphon the clear water from the beakers taking care not to disturb the sediment on the bottom of each beaker. Replace the beakers underneath the appropiate containers for second run.

18. Remove the sheet metal sleeves and inspect each soil sample to determine if sample has to be pushed up. If specimen has to be pushed up, make sure the lowest eroded portion of the sample is at least 1/4" above the top of the metal collar.

19. Repeat Steps 1-13 for the second run.

20. After cleaning the box, disassemble the test apparatus. Remove each sleeve into a seperate plastic bucket (Make sure you know which numbered sleeve is which that is in each bucket)

21. Clean the soil that has splashed onto the metal sleeves with the wash bottles and clean out the containers into an appropiate bucket. Wash out all eroded soil from these steps into an appropiate beaker.

22. Repeat the procedure for the remaining two samples.

23. Return all beakers to the machine until next day.

24. Take photographs of the eroded samples. Make up cards with the specimen number on them. Record roll number and frame number of each shot. Take 3 close-up shots of the surface of each specimen with the close up lens. Next take two pictures of two specimens paired together with the other lens. Finally take an overall photograph with the normal lens of the camera. (See Sample Notes)

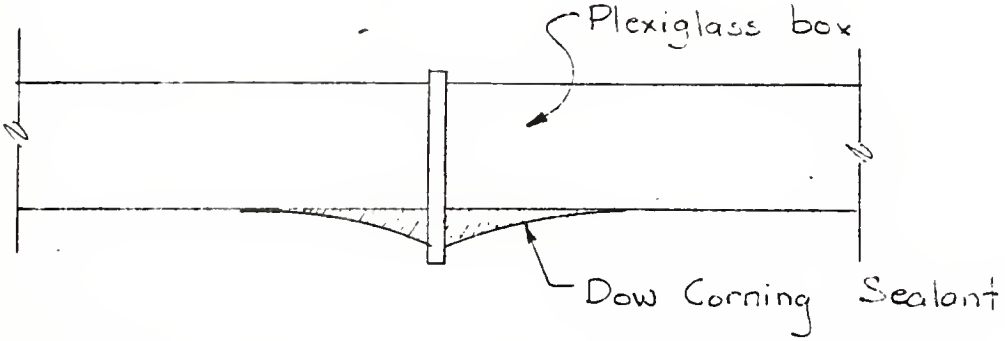
25. Clean out all equipment in preparation for the next test.

26. Next day: Siphon the water from each beaker and transfer the sediment to individual drying containers.

27. Dry for ≈ 2 days and weigh the oven dried soil. Calculate the erosion per area for each sample and average the values (See Sample Notes)

C MISCELLANEOUS

1. Repair of tubing Leaks:



Remove old sealant with razor blade. Apply new coating of sealant with small paintbrush making sure that during application the sealant does not cover opening of tubing. If sealant covers tubing opening, use one of the pins to reopen tubing. Repeat process for all other tubing that are defective

2. Priming the Pump: Occasionally the reservoir tank on the top of the apparatus may completely drain due to rough transfer of the hoses. If this happens, the pump will not be able to pump the water up to this level.

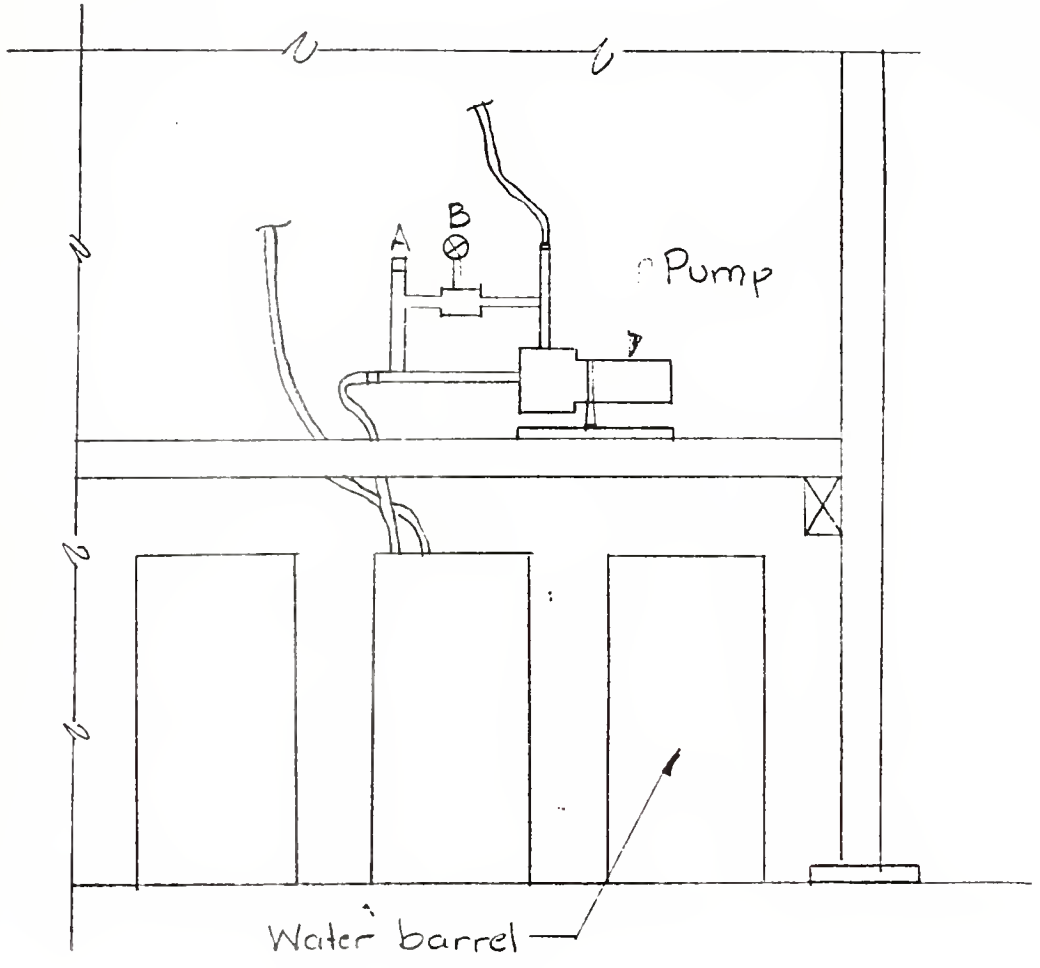


FIG. 6

Referring to Fig. 6 - To prime pump, close Valve B completely and open pipe at point A with a wrench. Fill the system at point A with water until overflowing condition occurs. When overflowing occurs QUICKLY close the system at point A and turn the pump on. Immediately after pump is turned on open valve B 3 revolutions. Check to see if water is pumping to upper reservoir. If no pumping occurs repeat process several times.

Valve B regulates the flow of water that is being pumped to the upper reservoir. Closing

Valve B completely would produce a "geyser" effect when the pump is turned on. Opening valve B 3 revolutions will regulate the flow to the upper reservoir without producing the "geyser" effect.

3. Changing Water Filters: there are two filters that have to be changed. One is located directly underneath the upper storage reservoir and the other is located near the water barrels. The filter at the upper reservoir should be changed every two months while the one located near the water barrels may be changed once every four months.

SAMPLE NOTES

Test Date	March 19 - 20		
Age of Specimen	Treated Blue Clay Till, 1% Lime, 3 day		
Specimen Number	188	189	190
Mold Number	16	21	22
Wt. of Mold & Comp. Soil (gm)	1479	1488	1474
Wt. of Mold (gm)	1089	1100	1090
Wt. of Moist Comp Soil (gm)	390	388	384
Wt. of Dry Soil (gm)	351	349	345
Dry Density γ_d (gm/cm³)	1.70	1.69	1.67
Container Number	1	2	3
Wt. of Container & Eroded Soil (gm)	248.60	266.01	183.96
Container Wt (gm)	230.74	239.34	160.50
Wt. of Eroded Soil (gm)	17.86	26.67	23.46
E.S./Area	0.220	0.328	0.289
$\frac{\Sigma}{3}$	0.279 gm/cm²		

30 blows

ω = 11.2%

$$W_{DRY} = \frac{W_{MOIST}}{1+\omega} \qquad \gamma_d = \frac{W_{DRY}}{Vol.}$$

Vol. of Mold = 206 cm³

Area of sample = 81.2 cm²

Wt. of molds are tabulated

Drying containers have been weighed previously

SAMPLE NOTES

March 19 Treated Blue Clay Till 9:30am → 10:30am
30 blows, 1% Lime, 3days

#1 825 ml } rain
#2 795 ml } guages

Temp = 20.5°C
H = 12.5 cm
R = 4 rev of Needle Valve

March 20 6:55am → 7:55am

#1 900 ml
#2 860 ml

T = 21.5°C
H = 12.5cm
R = 4 rev.

Photographs

Roll #	Frame #	Description
25	1	Specimen 188-190 — Treated Blue Clay Till, 1% Lime, 30 blows, 3 day cure
	2	Specimen 188-190
	3	Specimen 188-190
	4	Specimen 188-189
	5	Specimen 189-190
	6	Overall View 3-20-74 9:45am
	7	Another Test
	8	Another Test
	9	Another Test
	10	Another Test
	11	Another Test
	12	Another Test

PART II

RESULTS OF SOIL STABILIZATION TESTING

PART II - RESULTS OF SOIL STABILIZZTION TESTING

INTRODUCTION

This interim report presents the results of the first portion of a larger research study, this portion involving (a) the design, development, and testing of rainfall simulation equipment specifically aimed at facilitating comparisons of erosion resistance of a large number of soils stabilized in different ways, and (b) preliminary evaluation of the effectiveness of modest percentages of known soil stabilizing agents (hydrated lime and type I Portland cement). In addition, investigations were carried out aimed at characterizing the mechanisms of erosion under the impact of rainfall, and the effects of the stabilizers used on these erosion mechanisms. The design, development, and testing of the rainfall simulation equipment and the associated sample preparation and test devices has been described in Part I. In Part II we describe our experimental results as of November, 1973, and our interpretations of them.

As indicated in Part I of this report, soil erosion is a process of detachment and transportation of soil material by water or wind. In the present part of the report we document the effectiveness of several stabilizers in reducing or preventing soil detachment by water under simulated rainfall testing. Additional work described includes measurements of aggregate size distributions by wet sieving, pore size distributions by mercury porosimetry, and both macrophotography and scanning electron microscopy of the eroding soils. These additional investigations are helpful in evaluating the mechanism of erosion resistance developed.

Experimental Details

Soils and stabilizers used

Two primary soil materials were used in the investigations to date. One of these is an illite-containing commercial clay called "grundite" (supplied by Illinois Clay Products Co., Lansing, Ill.). Grundite is a "soil" material which has often been studied in investigations of the behavior of clay soils. The other soil material is derived from a naturally occurring soil described as the Crosby series in the pedological classification currently in use, and represents the 'B' horizon of the soil profile. The Crosby series is a till-derived soil of widespread occurrence in Indiana and neighboring states and its engineering properties have been extensively documented in various prior research studies carried out at Purdue University. Future work is programmed to include a significant number of additional types of soil materials.

Some of the relevant physical characteristics of the two soil materials used in the present study are given in Table 1.

Table 1. Soil Physical Characteristics

Parameter	Grundite	Crosby 'B'
Clay content (%)	64	20
Liquid limit (%)	56	28
Plastic limit (%)	32	20
Plasticity Index (%)	24	8
*Max. dry unit wt. (lbs/ft^3)	100	107
*Optimum moisture content (%)	20.0	19.0

*Under standard Proctor compaction, ASTM Designation: D 698-70, Method A.

The grundite soil material contained illite as its dominant clay mineral, with the presence of kaolinite also noted on X-ray diffraction analysis. The clay fraction of the Crosby soil was found to include a considerable content of montmorillonite, some mixed layer clay, and a relatively small content of kaolinite.

The Portland cement used in these experiments was a standard Type I cement supplied by Lone Star Industries. An analysis is provided in Table II.

Table II. Chemical Characteristics of the Portland Cement Used

Analysis:		Potential Compound Composition:	
SiO_2	21.42%	C_3S	49.9%
Al_2O_3	5.68	C_2S	23.9
Fe_2O_3	2.34	C_3A	11.1
CaO	64.41	C_4AF	7.1
MgO	1.07		
SO_3	2.84		
Na_2O	0.10		
K_2O	0.84		
Ignition loss	1.22		
Insoluble Residue	0.24		

Two types of hydrated lime were used in various portions of the work, a chemically pure (reagent grade) calcium hydroxide supplied by the Mallinckrodt Co., and a commercial partly dolomitic lime; the latter was observed to be considerably carbonated on X-ray examination.

One of the characteristics of soil materials that influences their reactions with stabilizing agents is their acid-base character. It was found that the pH of a 50% soil - 50% water slurry of the Grundite material was 2.7, indicating a very strongly acid reaction. It is not known whether the acidity is due to residues of strong acid used in processing the clay in commercial production or whether the clay is derived from naturally acidic shale deposits, but the strong acidity of its reaction indicates that added lime or cement will probably be relatively ineffective until the excess acid is neutralized. The Crosby soil is only slightly acidic, a 50% soil - 50% water slurry yielding a pH of 5.8; this slightly acid pH is reasonably representative of many soils.

Preparation of specimens for erosion tests

Desired weights of air-dried soil material and stabilizer are blended for 15 minutes in the dry state using a Patterson-Kelley twin-shells blending mixer similar to those used for commercial processing of various solid-liquid mixtures. This equipment has been found to give exceedingly uniform and efficient mixing of solids and incorporation of water without the problems associated with more commonly used drum or pan mixers. After mixing the dry constituents water is added through the spray device incorporated with the equipment and the solid and water are blended for an additional 15 minutes. Trial batch studies indicate that the resulting mixtures are exceedingly uniform in both water and stabilizer contents.

The amount of water added is that previously determined to yield the optimum moisture content for the soil as given in Table 1. Specimens

are then compacted using the standard Proctor hammer in specially fabricated split molds that are 4 inches in diameter and 1 inch in height. The number of blows applied is that calculated to deliver the same applied energy per unit volume of soil as is delivered in standard Proctor compaction (ASTM Designation D-698-70, Method A). The dry unit weights obtained are closely comparable to those obtained in the standard test.

The compacted soil-stabilizer specimens are sealed in plastic sacks and cured at 74° F. in a fog room without being removed from their molds. Curing is carried out for periods ranging from 1 day to the maximum desired. One of the points of interest in the research is characterization of the time required to develop the erosion resistance with the various treatments examined.

Erosion tests

The standard erosion test used here consists of exposure to successive rainfalls of intensities of approximately 3.25 inches per hour for one hour on each of two successive days. Specimens are run in triplicate. Soil detached from the specimens is recovered, dried, and weighed, and the soil loss per cm^2 of exposed soil surface is calculated and used as the index of erosion for the particular treatment employed. The results for the 3 replicate specimens are averaged for the final figure. The procedure for the tests is described in detail in Part I of this report.

Aggregate size analysis by wet sieving

The soil or stabilized soil in its compacted and cured condition is passed gently through a U.S. Standard No. 4 sieve (4.76 mm opening) to break up the material. A sample weight of 25 grams (moist weight) of

this broken up material is then placed over a nest of sieves containing successive sieves sized to retain grains larger than 2 mm, 1 mm, 0.5 mm, and finally 0.21 mm. The nest is then placed on a specially-designed shaker which moves the sieves up and down under water. The action provides a uniform stroke of 1.5 inches and a frequency of 30 cycles per minute. The underwater sieving is carried on for a 30-minute period, after which the soil aggregations retained on each of the sieves is dried and weighed. The weight retained on each sieve is divided by the oven-dry weight equivalent to the 25 gram original moist weight to yield the weight percent of soil retained on that sieve. The procedure has been extensively described in the literature (1,2,3,4) and is quite useful in providing a measure of the formation and retention of water-stable aggregations of clay particles. The data can be used to define a single-parameter "aggregation index", which is the weighted mean diameter of the aggregated soil after the test as compared with that of the same soil in a completely dispersed condition (4).

Pore size distributions

Mercury intrusion measurements were applied to the determination of the pore size distributions of the stabilized soils following the procedures described by Diamond (5). Selected samples of soil and stabilized soil dried at 105° C, evacuated, and subjected to the mercury penetration measurements at increasing pressures of up to 15,000 psi. The results were converted to pore size distributions by the usual method, with a surface tension of mercury of 484 dynes per cm^2 and a contact angle of 147° being used in the calculations.

Macrophotography

The appearance of each of the specimens after exposure to the test rainstorms was recorded using an "Insta-Tech" short-focus camera similar to the common "Instamatic" cameras but designed specifically for routine laboratory photography.

Scanning Electron Microscopy

Specimens of compacted soil and of stabilized soils were secured both before and after application of the rainfall tests. Specimens exhibiting surfaces that had been exposed to rainfall and others showing fracture surfaces so as to reveal the internal soil structure were secured. After drying at 105° C and fracturing (if required) the specimens were mounted on standard metal stubs and coated in a vacuum unit with very thin films of carbon and gold to insure electrical conductivity. The coated specimens were then examined in a Jeolco SMU -3 scanning electron microscope equipped with an EDAX 707 energy-dispersive X-ray attachment. Photographs of features of interest and indications of X-ray spectra were obtained by the usual methods.

Results and Discussion

Erosion characteristics of unstabilized soil

All of the results for soil and for soil-stabilizer combinations reported in this study represent the erosion suffered by materials compacted at optimum moisture contents by a simulated Proctor compaction procedure as described earlier. The effectiveness of stabilization for soils or soil stabilizer combinations compacted at reduced compactive efforts or of uncompacted materials with stabilizers applied by unorthodox methods not involving compaction have been reserved for future investigations.

In consequence, evaluation of the effectiveness of a given stabilizing treatment can be simply made by comparing the erosion loss to that of the same soil compacted the same way but otherwise not stabilized. In other words, additive-free compacted soil of the same type serves as a base level or control against which the effects of the stabilization treatment can be compared. It should of course be recognized that this comparison is only for evaluation of the relative success of the stabilization treatment. In reality the compaction by itself may have considerable effect on erosion loss, the potential erodability of uncompacted soil probably being greater than that of soil properly compacted at its optimum moisture content.

The resistance to the standard rainstorm treatment described earlier was found to be slightly different for the two soils tested. It was found that under the standard regime the Crosby soil compacted at

optimum moisture content but not otherwise stabilized lost an average of 2.1 grams of soil per cm^2 of exposed surface. Under the same test conditions the compacted grundite soil suffered slightly less erosion loss, its value being 1.7 g/cm^2 of surface.

Macrophotographs reflecting the appearance of the specimens after exposure to the test rainstorms are given as Figures 1 and 2. The figures show the overall appearance of two of the three test replicates and a slightly magnified view of the details of the exposed surface of one of the specimens for each soil. The Crosby soil is clearly dispersed by the impact of the raindrops, and in one of the two specimens shown (test no. 49) erosion in the upper left hand corner has completely removed all of the soil, leaving some of the wire mesh support showing through. In the enlarged view individual sand and fine gravel sized-particles are visible and are free of any adhering clay or silt particles, the latter having been washed away. There is only slight evidence of residual aggregation of fine particles, most of the natural aggregations on the surface having been dispersed by the action of the raindrops.

The appearance of the grundite is slightly different. There are no sand particles in this clay-size material, but there seems to be a greater indication of residual small-scale aggregations of clay particles. The topography of the remaining surface is somewhat more pronounced, and erosion seems to be a more localized phenomenon, with rounded "canyons" being cut into the material. There seems to be little slumping with almost vertical walls having been formed in some areas. The appearance is reminiscent (in miniature) of the kind of topography that may be generated in loessial soils.

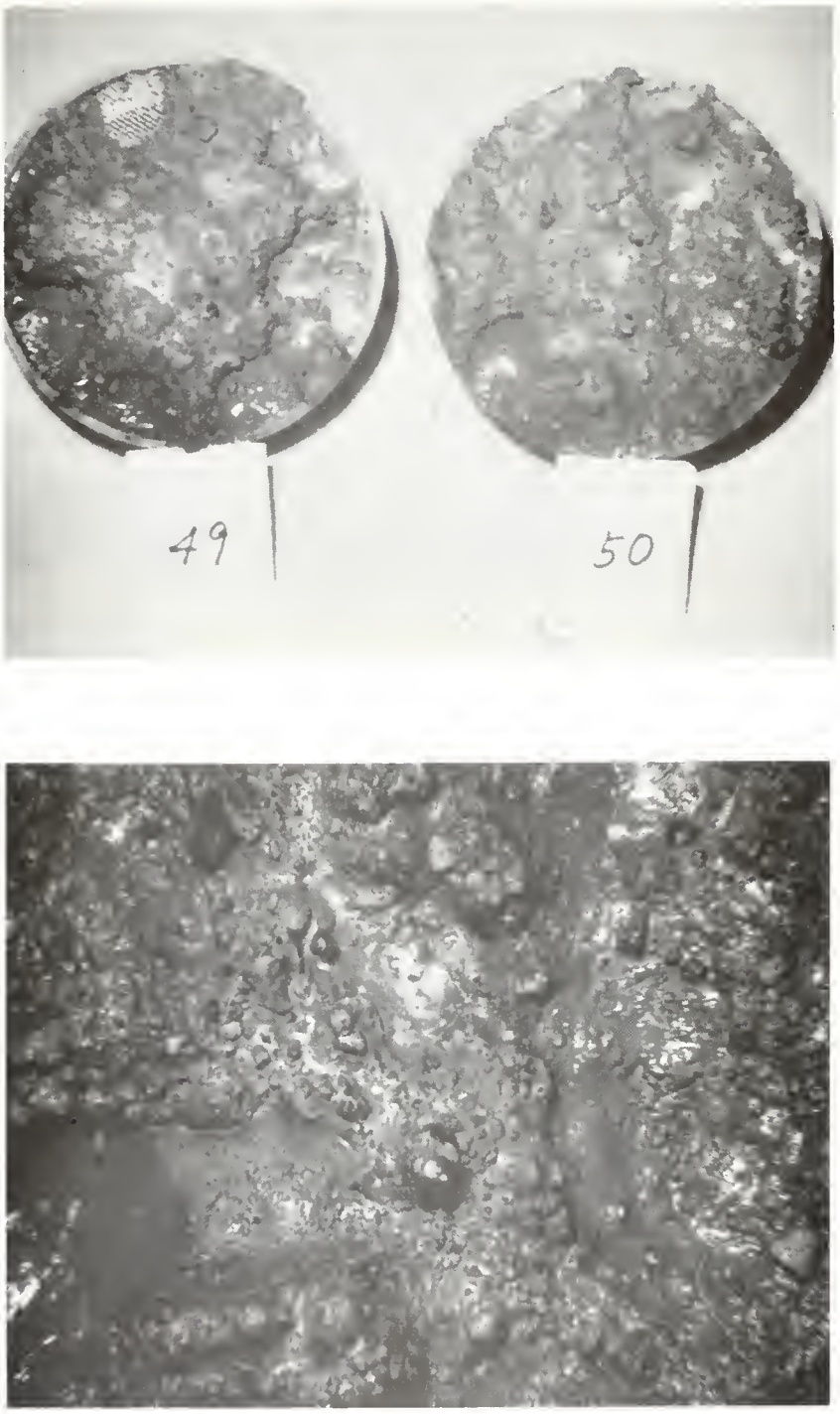


Figure 1. Surface appearance of additive-free Crosby specimens after exposure to test rainstorm.

Figure 2. Surface appearance of additive-free grundite specimens after exposure to test rainstorm.

The numerical soil erosion test results are quite consistent for the several replicates. Further, despite the real differences in appearance and perhaps in behavior between the two soils, the quantitative results (averaging 2.1 and 1.7 g/cm^2 of exposed surface) are sufficiently similar that one can take as a generalization that unstabilized compacted soils will lose on the order of 2 g/cm^2 of exposed soil by erosion due to raindrop impact in a standard test storm sequence of this type. Expressed in more practical units, this is equivalent to about 90 tons of soil per acre, and illustrates the potential extent of the problem of soil erosion from construction sites.

These figures provide the benchmarks for interpretation of the effectiveness of stabilization against soil erosion by rainfall. Corresponding losses suffered by properly stabilized soils should be very much less than this if the stabilization treatments are to be deemed successful.

Effectiveness of lime in reducing soil erosion

In a series of experiments the erosion resistance of the Crosby soil after additions of 1 percent, 2.5 percent, and 5 percent by weight of lime was investigated. The soils treated at the 1 percent and 2.5 percent levels were treated with reagent-grade lime, the 5 percent level treatment being with the relatively impure, carbonated commercial lime. Curing periods allowed prior to rainfall ranged from 7 to 21 days.

The results in terms of erosion loss are given in Figure 3.

It is clear from Figure 3 that the erosion loss of the Crosby soil is reduced drastically by as little as 1 percent lime in as little as 7 days curing time (earlier response was not tested). This treatment

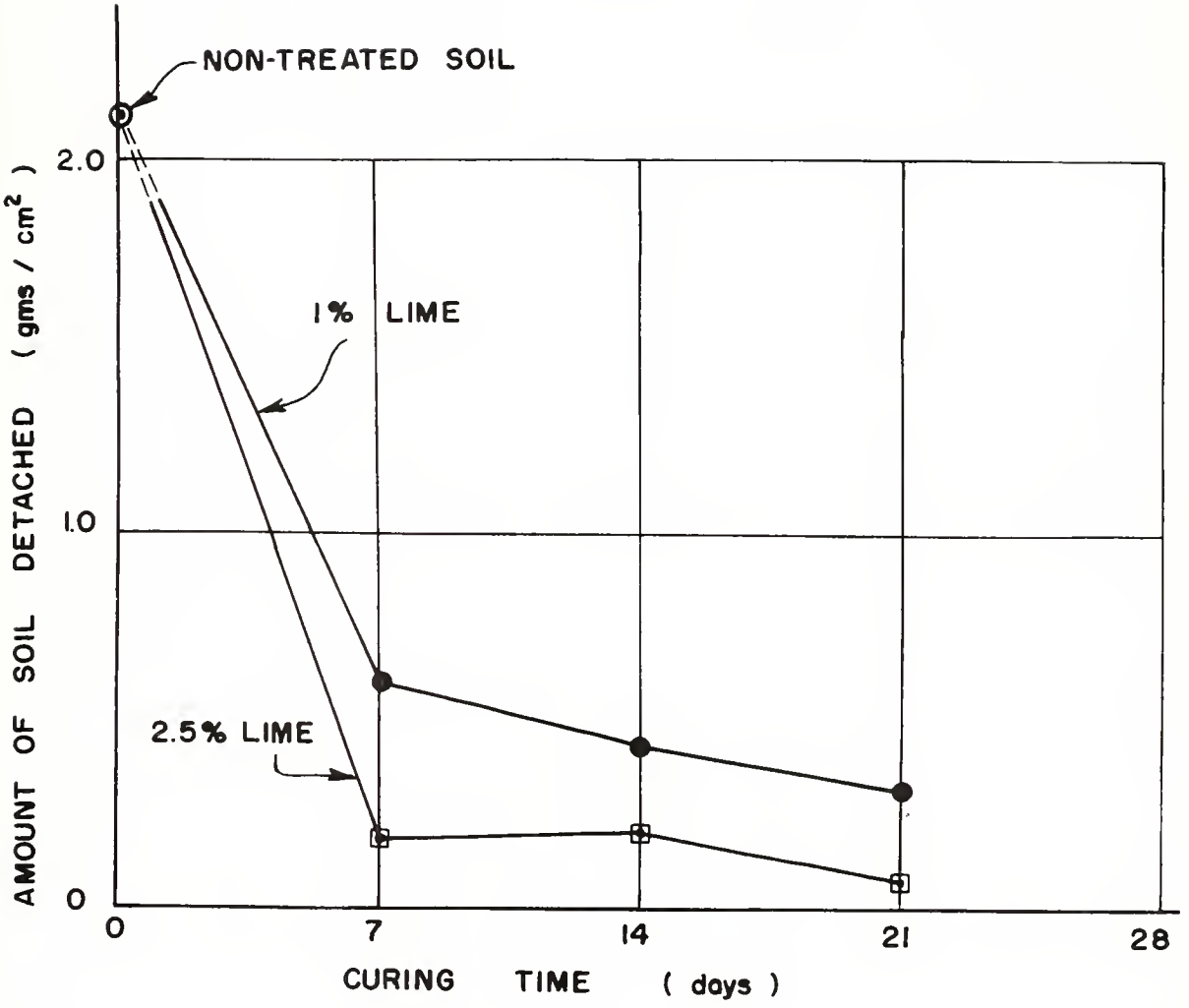


Figure 3. Erosion losses of lime-stabilized Crosby soil as functions of percentage of lime and of curing period.

cut the amount of soil detached and removed to less than one-third of that of the "control", i.e., the same soil compacted but not otherwise treated. Curing for an additional two-week period resulted in halving the value for the one-week period, and must be considered to have effected excellent stabilization against erosion loss.

The appearance of the specimens after having been subjected to the test rainstorms are illustrated in Figures 4 and 5. After only 7 days of curing, there are some remnant areas of the original specimen surface that have survived the rainstorm exposure, as indicated in Figure 4. Individual grains of coarse sand and fine gravel are not so clearly exposed, and much of the residual material on the surface seems to be aggregated into aggregations tbat have survived the exposure, although some slick spots are present indicating a partial dispersion of the clay into individual particles. After 21 days there seems to be more of the original surface retained, although this varies from replicate to replicate. Otherwise there is little observable difference in appearance arising from the aging process.

As indicated in Figure 3, use of a higher percentage of the same lime (2.5 percent) resulted in even stronger reductions in the amount of soil detached during the test rainstorms. For example, incorporation of 2.5 percent lime resulted in an erosion loss after a week of curing that was only one-third of that for the 1 percent treatment cured for the same period, amounting to only 0.2 g of soil per cm^2 of exposed soil surface. Further curing until 21 days reduced the loss even further, to a relatively insignificant 0.07 g/cm^2.

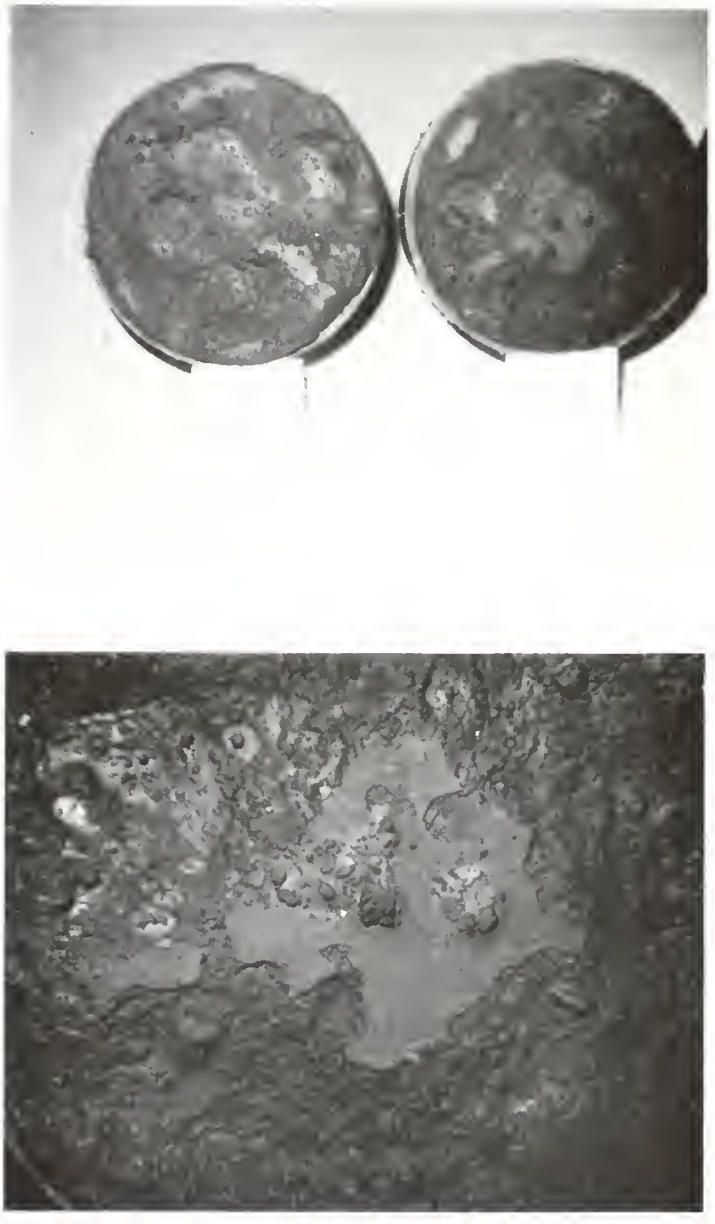


Figure 4. Surface appearance of Crosby specimens treated with 1% lime and cured for 7 days before exposure to test rainstorm. Average soil loss was 0.6 g/cm^2 of surface.

Figure 5. Surface appearance of Crosby specimens treated with 1% lime and cured for 21 days before exposure to test rainstorm. Average soil loss was 0.3 g/cm^2 of surface.

Figures 6 and 7 document the appearance of such specimens after the test rainstorms. It is apparent that with 2.5% lime substantially increased portions of the original specimen surface are preserved and the depth of soil removed is very much reduced, except perhaps at the perimeters of the specimens.

Thus it appears from the data that practical, satisfactory control of soil erosion resulting from the soil detachment process under severe rainstorms can be accomplished with quite small percentages of lime as a stabilizing agent.

However, it appears from other test results that the type of lime used does have some bearing on the effectiveness of the stabilization attained. Results were obtained for specimens of the Crosby soil treated with an impure commercial lime (a somewhat dolomitic, partly carbonated material) at the 5 percent level after a 7-day curing period. It would be expected that since 2.5 percent lime produces a significant decrease in erosion loss over that secured at 1 percent, a 5 percent treatment would improve the situation still further. This appeared not to be the case, 5 percent of the commercial lime yielding a soil erosion loss of about 0.4 percent, intermediate between those for 1 percent and for 2.5 percent of the pure lime after the same curing period. It is apparent that the commercial material used here is inferior to the reagent grade level as a stabilizing agent.

In view of the reduced effectiveness of the impure commercial lime compared to that of pure lime in stabilizing Crosby soil, it was expected that some reduction in effectiveness would also be manifested

Figure 6. Surface appearance of Crosby specimens treated with 2.5% lime and cured for 7 days before exposure to test rainstorm. Average soil loss was 0.2 g/cm^2 of surface.

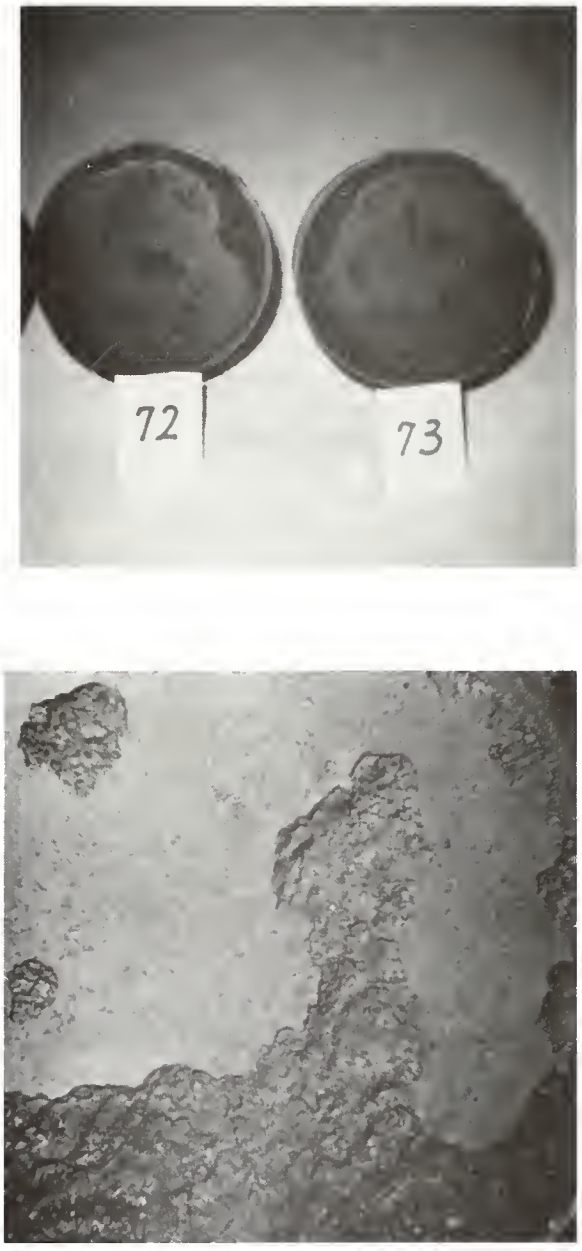


Figure 7. Surface appearance of Crosby specimens treated with 2.5% lime and cured for 21 days before exposure to test rainstorm. Average soil loss was 0.07 g/cm^2 of surface.

with the grundite soil. A comparison of the commercial lime with pure lime used at the 5 percent treatment level with grundite was carried out, and the results obtained are shown in Figure 8. As expected, 5 percent of the pure lime effectively stabilized this soil after a 7-day curing period (average loss 0.2 g/cm^2); further curing reduced the erosion still further. On the other hand, treatment with the impure dolomitic carbonated commercial lime was not only ineffective, it actually increased the amount of soil lost above that of the control additive-free specimens. Further, this increased soil loss became progressively worse with curing and by 14 days curing practically all of the soil present was eroded.

The contrast in appearance of the specimens was as dramatic as the contrast in numerical results. Figure 9 shows the almost perfectly stabilized character of the grundite stabilized with 5 percent of pure lime after 7 days curing. Figure 10 shows the markedly difference appearance of grundite treated with the same amount of the commercial lime and cured for the same period. Figure 11 illustrates the extreme soil loss suffered by the grundite treated with 5% of the commercial lime and cured for 14 days before exposure to the rainstorm. Almost all of the soil has been removed.

Investigations aimed at determining the cause or causes of this destabilization of grundite with the impure commercial lime were pursued and will be discussed subsequently. It appears that a major contributing cause is the high acidity of the grundite soil material, i.e., its low pH, which seems to have neutralized much of the commercial lime added before it could act as a stabilizer. It appears that natural soils, being far less acid than this commercial product clay material, will not

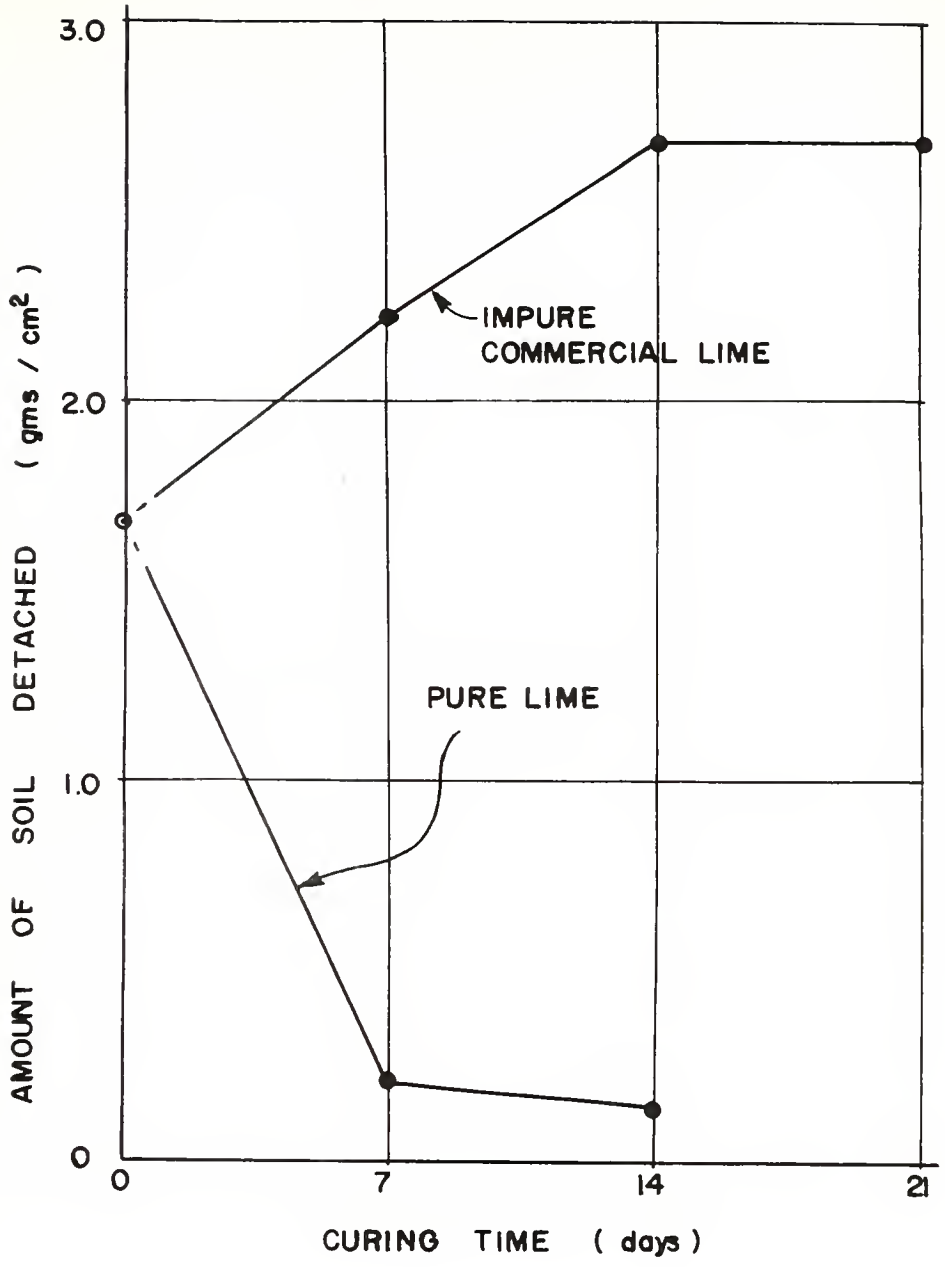


Figure 8. Erosion losses of grundite soil treated with 5 percent pure lime and with 5 percent impure commercial lime.

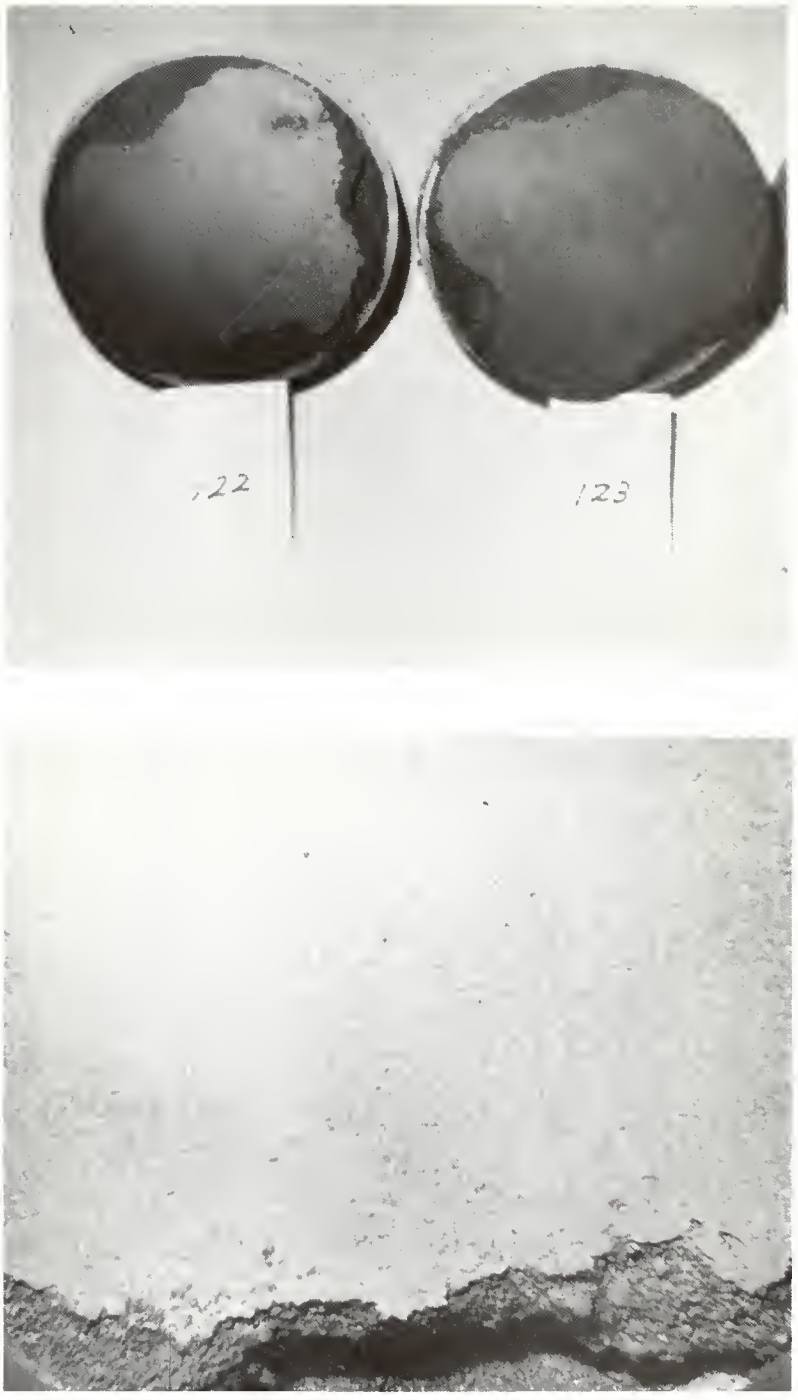


Figure 9. Surface appearance of grundite specimens stabilized using 5% pure lime and cured for 7 days prior to test rainstorm. Average soil loss was 0.2 g/cm^2.

Figure 10. Surface appearance of grundite specimens treated with 5% impure commercial lime and cured for 7 days prior to test rainstorm. Average soil loss was 2.2 g/cm^2.

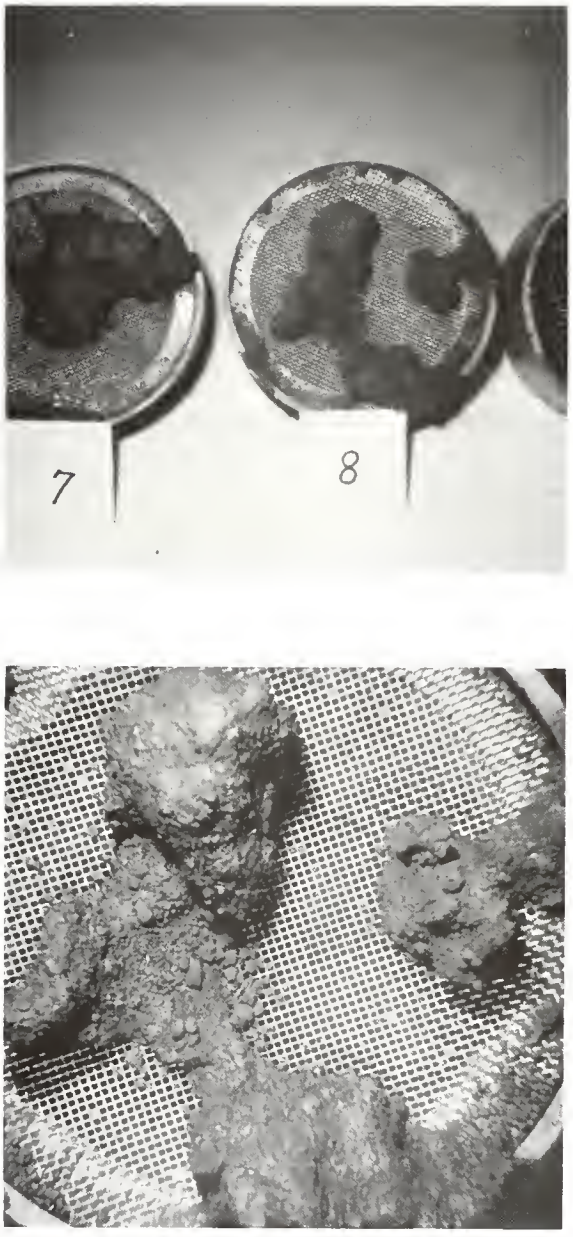


Figure 11. Appearance of grundite specimens treated with 5% impure commercial lime and cured for 14 days prior to test rainstorm. Average soil loss was 2.7 g/cm^2.

normally yield such negative response to lime, even though the response to be expected from low quality commercial lime may not be as good as it would be to pure uncarbonated calcitic lime.

Effectiveness of Portland cement in reducing soil erosion

The erosion losses suffered by specimens of the Crosby soil treated with 1 percent and 2.5 percent Type I Portland cement are plotted in Figure 12. Similar data for the grundite soil are given in Figure 15.

It is immediately apparent from Figure 12 that treatment of Crosby soil with 2.5 percent cement effectively and rapidly stabilizes it against erosion loss. The loss suffered after a curing period as brief as 1 day is negligible, and further curing is obviously not required. The appearance of such nearly perfectly stabilized specimens is illustrated in Figure 13.

As indicated in Figure 12, treatment of this soil with cement at the 1 percent level also accomplishes virtually complete stabilization against erosion, but only after a somewhat prolonged curing period of 28 days. The soil lost after 7 days cure is still about half that of the additive-free control, hardly well enough stabilized for effective erosion prevention. The appearance of specimens at this stage is illustrated in Figure 14. It would seem that a practical cement content for stabilizing the Crosby soil would be of the order of 1.5 or perhaps 2 percent, and at these percentages one should expect rapid development of resistance to erosion.

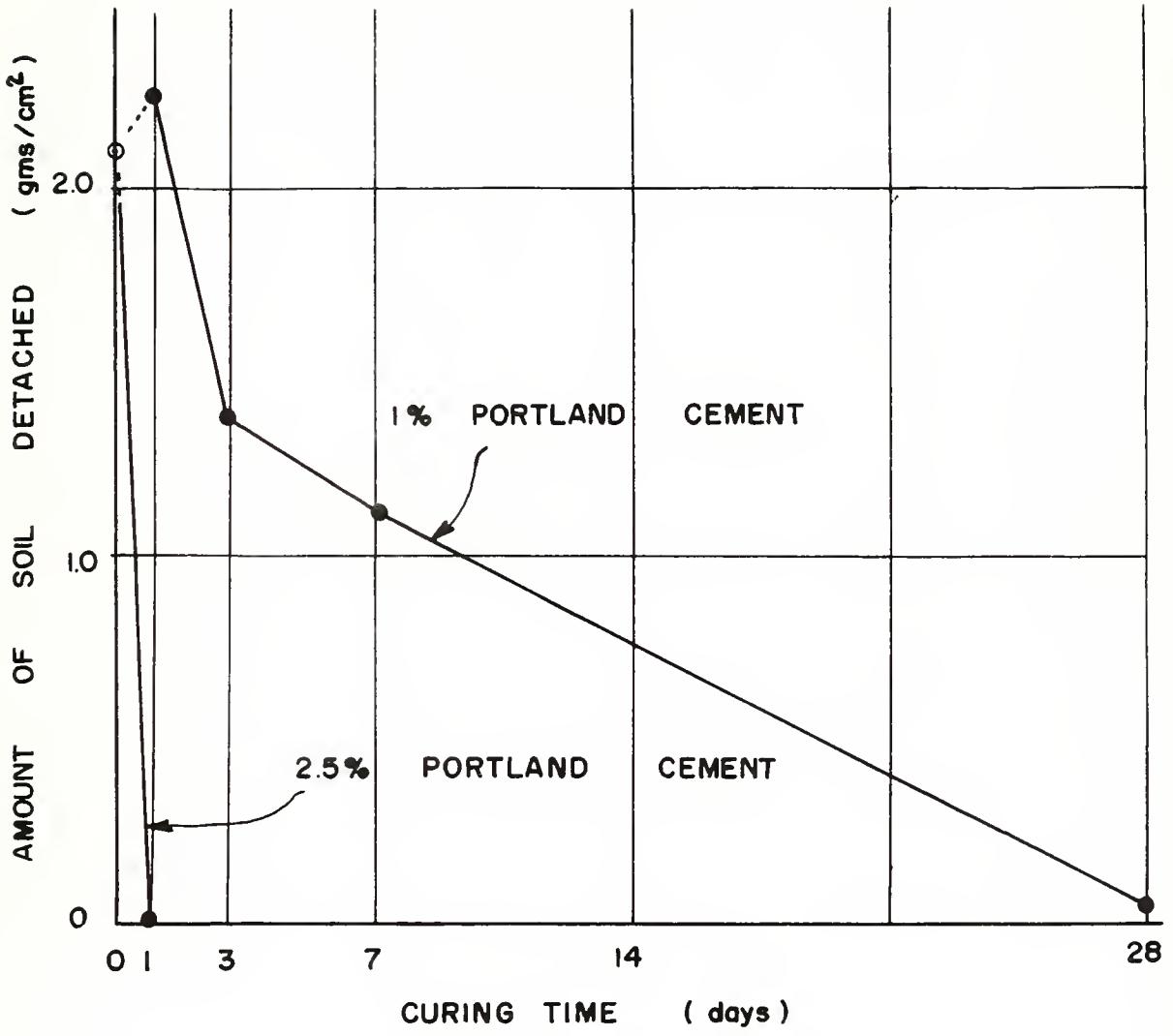


Figure 12. Erosion losses of cement-stabilized Crosby soil as functions of percentage of cement and of curing period.

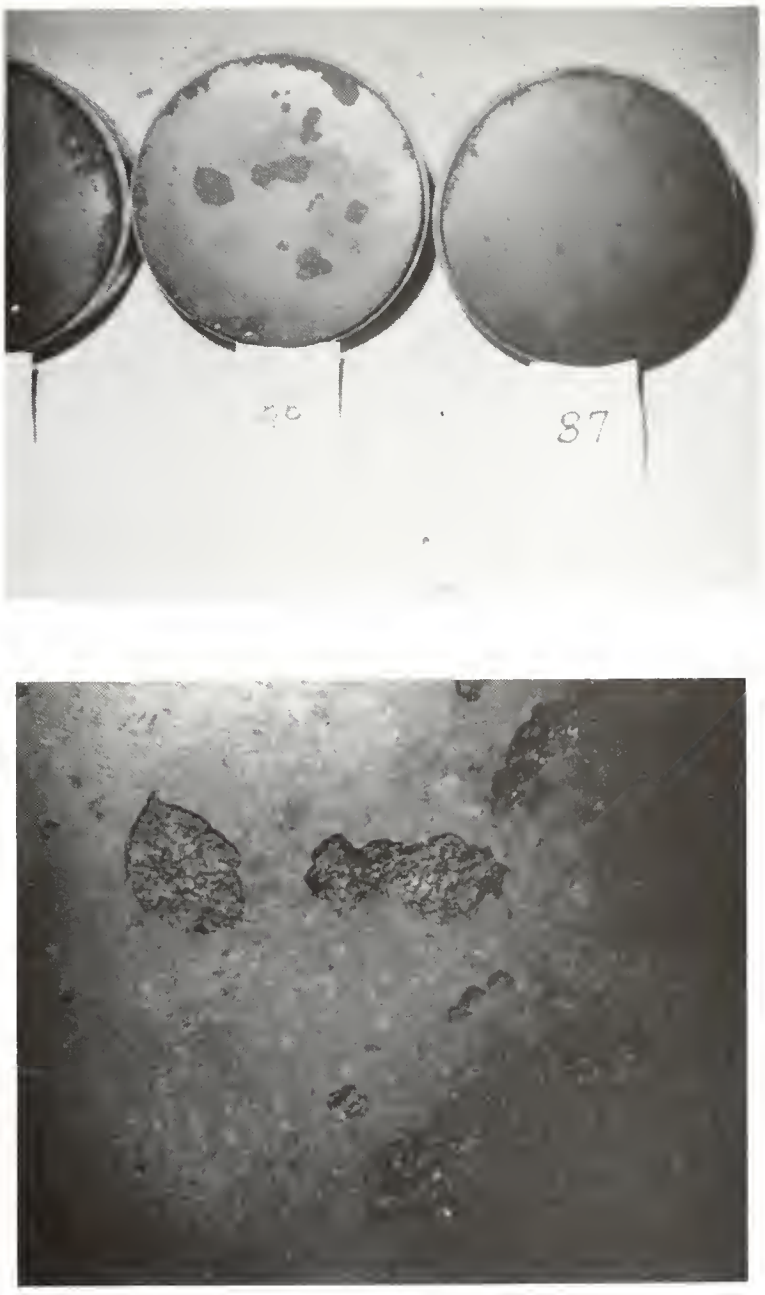


Figure 13. Surface appearance of Crosby specimens stabilized with 2.5% Portland cement and cured for 1 day prior to exposure to test rainstorm. Soil loss negligible.

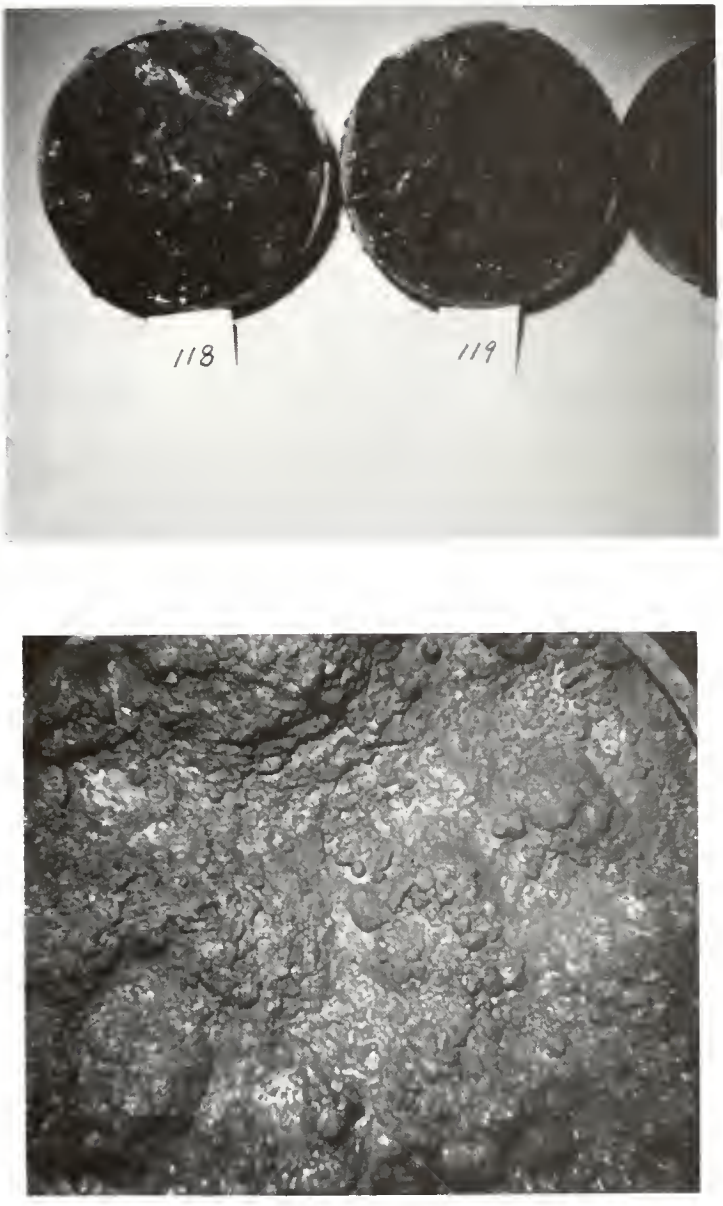


Figure 14. Surface appearance of Crosby specimens stabilized with 1% Portland cement and cured for 7 days prior to exposure to test rainstorm. Average soil loss 1.1 g/cm^2.

The effectiveness of Portland cement in stabilizing grundite soil is also a function of the treatment level, as indicated by the results shown in Figure 15. For this acidic clay material, treatment at the 5 percent level results in excellent stabilization (erosion loss 0.2 g/cm^2) but only after a 3-day curing period. Exposure after 1 day results in destabilization, that is, loss significantly greater than that of the additive free control. The contrast in appearance between specimens exposed after 3 days and after only 1 day of curing is apparent in Figure 16.

Treatment at a level of 2.5 percent cement seems to be inadequate, with grundite, even after prolonged curing. The data of Figure 15 indicate that there is an initial destabilization, that is, an enchancement of erosion loss over that of the additive free control, but in this case the period involved is prolonged to at least two weeks of curing; even after 28 days the soil loss is only slightly less than that of the control. The appearance of such inadequately-stabilized specimens is indicated in Figure 17.

The temporary destabilization of the grundite with small amounts of Portland cement seems to be related to the similar effect produced on grundite with the impure commercial lime, and undoubtedly reflects the same set of causative factors. It was reasoned that the mechanism involved must relate to the high acidity of this clay, in terms of its potential for neutralization of lime and lowering of the hydroxl concentration that would otherwise be produced.

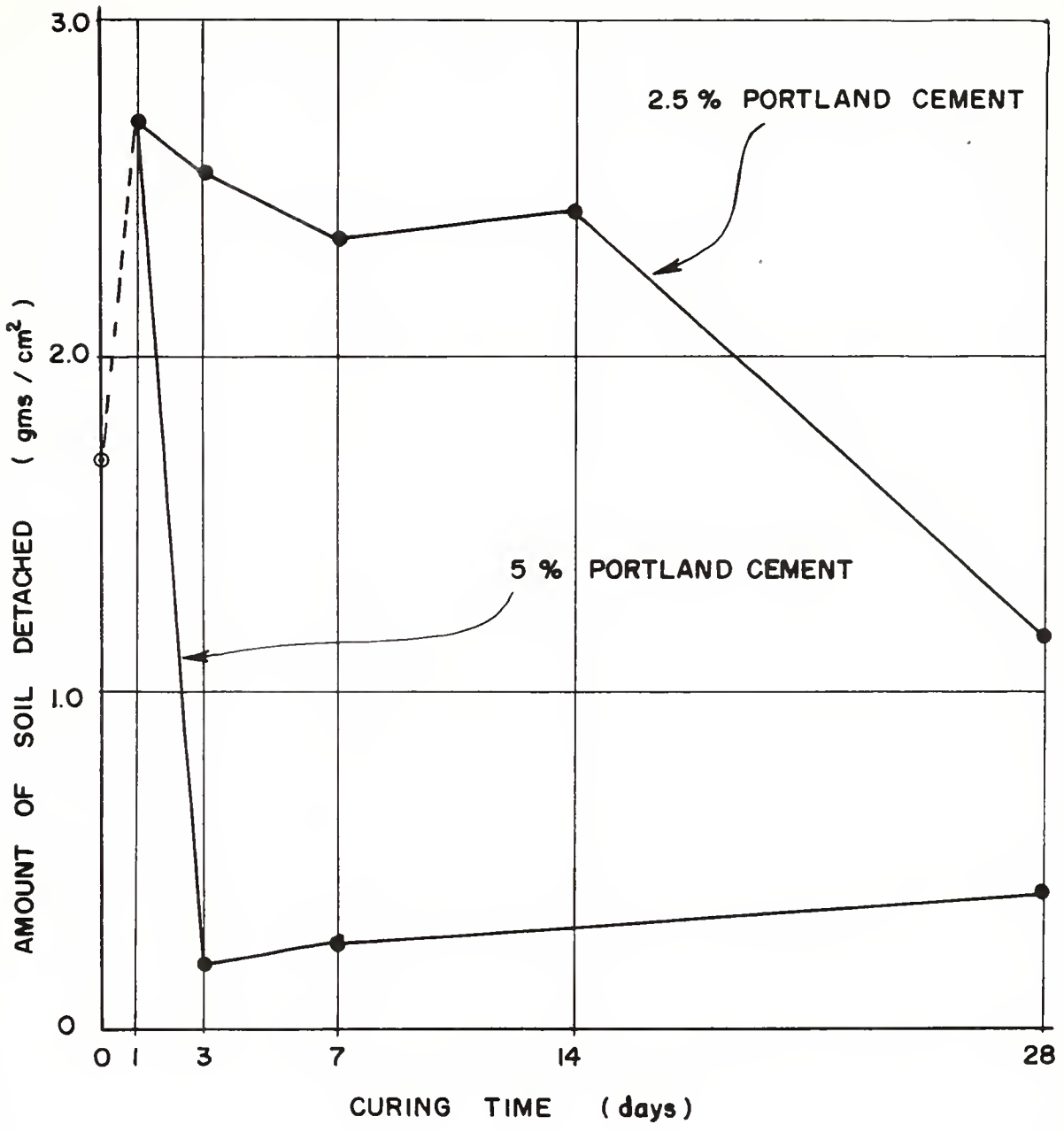


Figure 15. Erosion losses of Portland cement-stabilized grundite soil as functions of percentage of cement used and of curing period.

Figure 16. Effect of curing period on appearance of grundite specimens stabilized with 5% Portland cement. Left: specimen cured 3 days before rainfall exposure (soil loss 0.2 g/cm^2). Right: specimen cured 1 day before exposure (soil loss 2.7 g/cm^2).

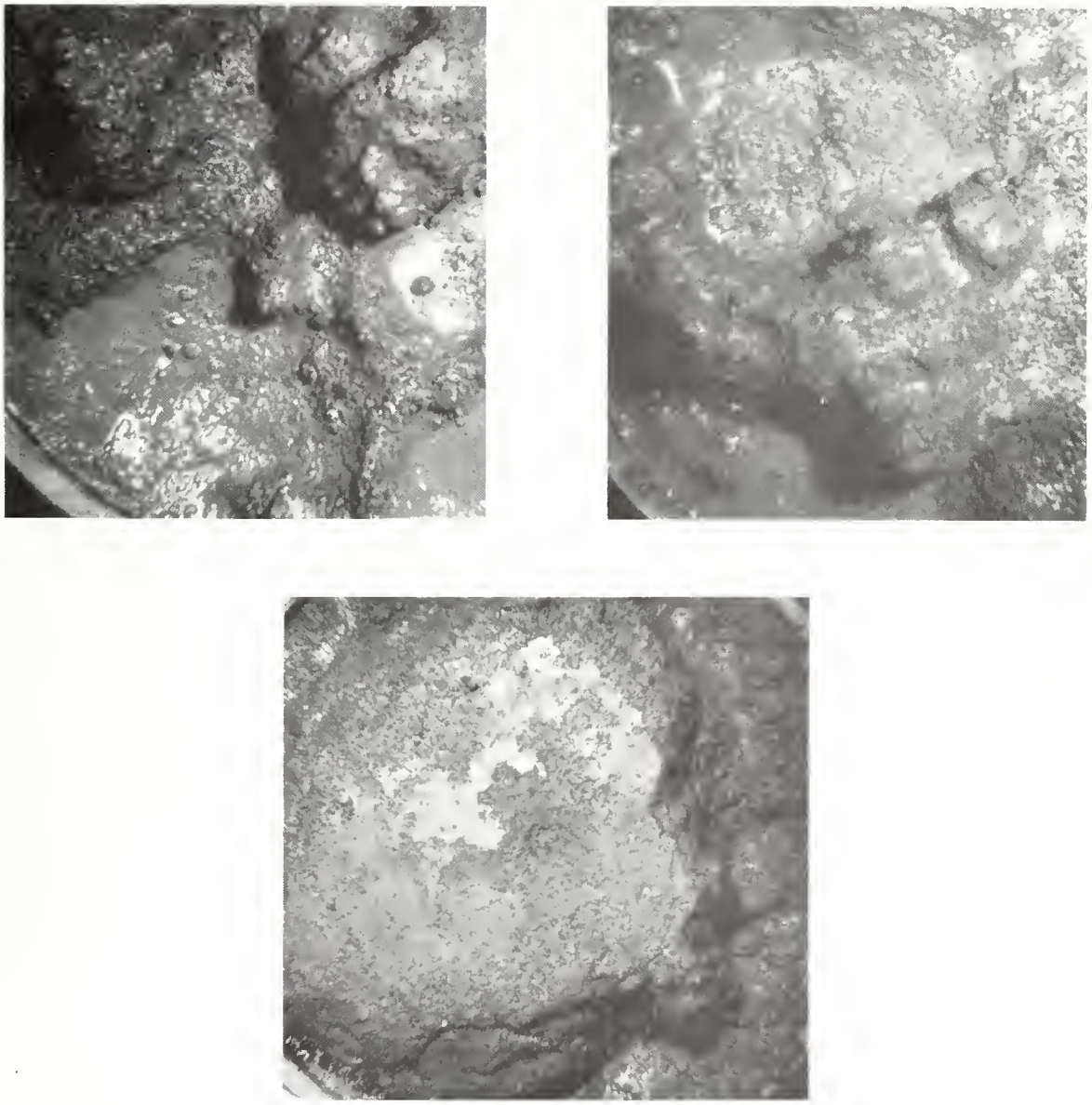


Figure 17. Appearance of grundite soil inadequately stabilized with 2.5% Portland cement. Upper left: 1 day cure, soil loss 2.7 g/cm^2. Upper right: 14 days cure, soil loss 2.4 g/cm^2. Lower: 28 days cure, soil loss 1.2 g/cm^2.

pH measurements and their interpretation

The influence of the hydroxyl ion concentration in the soil water on the stabilization process has been appreciated for some time, particularly with respect to lime stabilization. Usually this factor is expressed in terms of pH (the logarithm of the reciprocal of the hydrogen ion concentration, the product of hydrogen and hydroxyl ion concentrations being a constant of roughly 10^{-14}). Eades and Grim (6) proposed a quick test for use in determining the amount of lime required to mechanically stabilize a particular soil, which consists of measuring the pH of a series of soil-lime-water slurries to determine the minimum lime necessary to generate a pH of 12.4 (that of a saturated lime solution) in 1 hour. Evaluation of the test in terms of the unconfined compressive strengths of stabilized soils produced by mixtures generating various pH levels has been carried out by Thompson and Eades (7), who concluded that "the quick test requirements reasonably and conservatively indicates the lime requirement for stabilizing a fine-grained soil." The test has been adopted for design of stabilized highway subgrades by at least one state highway department, and in modified form by others.

It should be realized that stabilization of soil for the purpose of resisting erosion by rainfall presumably does not set as stringent a requirement as stabilization for the development of mechanical strength in a highway subgrade. Thus, the 12.4 pH requirement is undoubtedly too conservative from the point of view of erosion control. In the opinion of the present writers, pH values of the order of 11.4 or so may indicate that sufficient lime has been used for stabilization against rainfall erosion.

A series of pH checks were carried out using the grundite and Crosby soils mixed with both the pure reagent lime and with the impure commerical lime. These measurements were made under slightly different conditions than those proposed by Eades and Grim, a lower water content of the slurry being the main difference, but this should not seriously preclude the interpretation of the present data for comprative purposes.

The pH of the water used was measured as 7.1. The initial pH of additive-free grundite slurry was only 2.7 initially and 2.9 after 24 hours of standing. This is extremely strong acidity, well beyond the range of almost all natural soils. The Crosby soil yielded a pH of 5.6 initially, reaching 5.8 after 24 hours.

The pH values measured on slurries with 5 percent lime by weight of soil are given in Figure 18. The data indicate that while none of the mixtures reach the 12.4 pH value required in the quick test of Eades and Grim, the use of pure lime with either soil brings about an immediate pH increase of 11.4 and a further increase with curing. This appears to be an acceptable level for stabilization against erosion loss. With the impure commercial lime, the immediate pH obtained with the grundite soil was barely above neutrality (pH 8), and even after 24 hours only increased to 10.1. The pH for Crosby soil with this lime remained low only for about an hour; for this initial interval it was similar to that recorded with grundite. Shortly thereafter it began to increase rapidly, and reached a probably effective level (11.4) in about 1-1/2 hours.

It may be recalled that the use of 5 percent of pure lime with grundite effectively stabilized this material against erosion but that

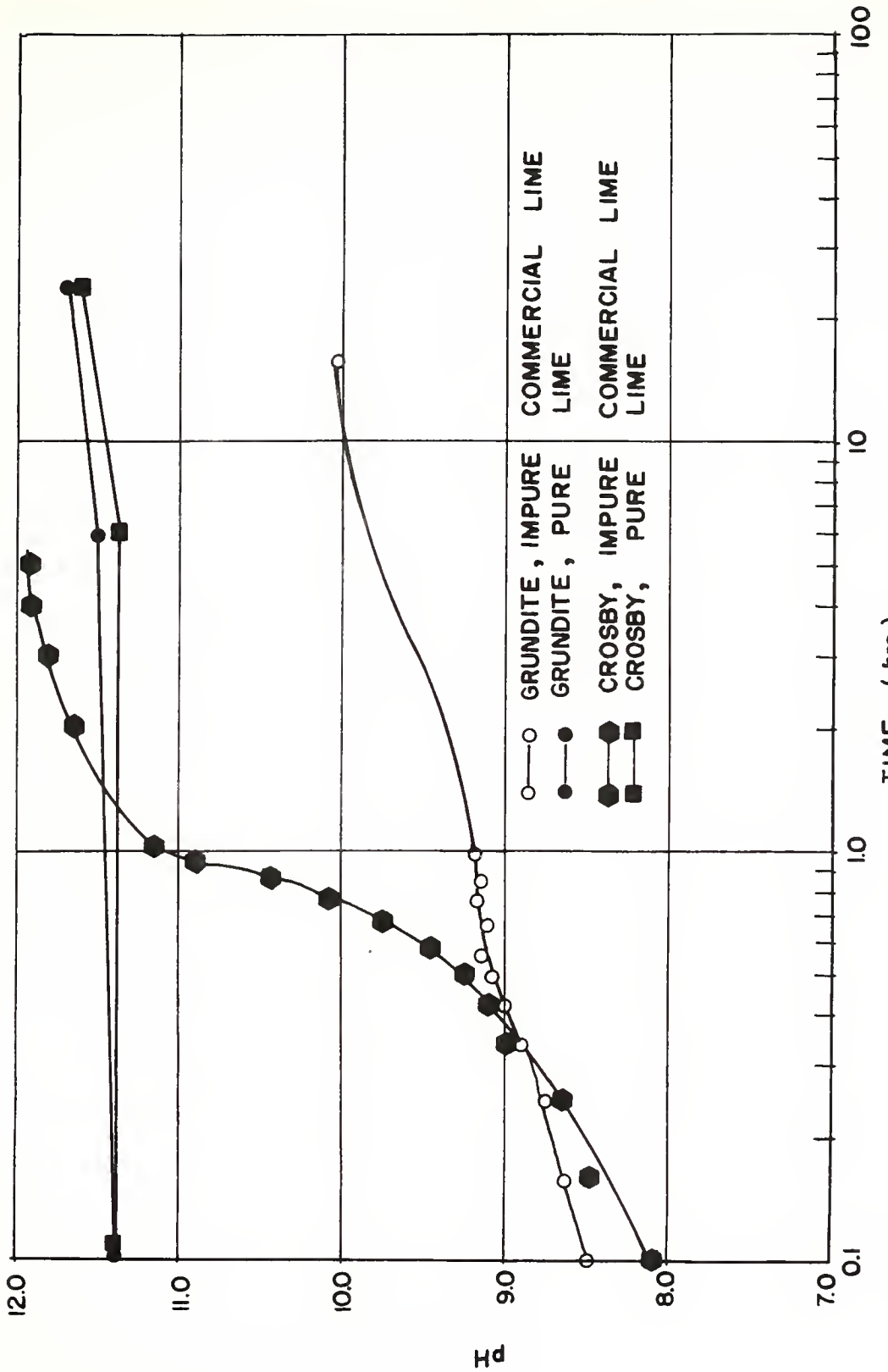


Figure 18. pH of soil - stabilizer - water slurries as a function of time (expressed on a log scale).

5 percent of the commercial lime resulted in destabilization, that is, erosion loss even greater than that of the additive-free grundite. It is now apparent that the commercial lime was simply insufficient to increase the pH to the level required for effective chemical reaction with the soil particles and hence no such reaction (or very little of such reaction) could have taken place. However, the increase in pH attained was certainly sufficient to at least partly deflocculate the grundite particles when dispersed in water and this partial physicochemical deflocculation in going from strongly acid to slightly alkaline conditions is a reasonably, if probably incomplete, explanation for the destabilization.

For the Crosby soil, no such problem was encountered. The soil is only slightly acidic, and apparently there is little difficulty overcoming this small degree of acidity and bringing the pH up to that required for chemical reaction with the soil particles. Presumably almost all natural soils will behave like the Crosby rather than like the grundite soil.

A certain degree of destabilization was observed for the grundite soil mixed with Portland cement, as was shown in Figure 15. This lasted only a brief interval (one day) at the 5 percent cement level, and was followed by effective stabilization by 3 days. At the 2.5 percent cement level the destabilization was prolonged, and only partly overcome even after 28 days. A check on the pH of grundite-cement slurries was made. At the 5 percent cement level, the values recorded were 10.5 initially, and rising to 11.1 at 6 hours and 11.3 at 24 hours, i.e., marginally satisfactory after some hours of reaction. In contrast to this, at the

2.5 percent cement level the initial value was only 8.9, rising only to 10.5 at 6 hours and remaining at 10.5 after 24 hours. While stabilization with cement involves a much more complex set of reactions than stabilization with lime, it appears that pH is perhaps euqlly important, and that a pH of 10.5 is inadequate. The Crosby soil responded to cement with no difficulty at the 2.5 percent level (Figure 12), and the pH of corresponding mixtures reached 11.2 by 6 hours. Thus it appears that the development of a similarly high pH is a necessary indicator of success in cement stabilization for erosion control as it is in lime stabilization.

Analysis of the aggregate size distribution of additive-free soils.

The distributions of sizes of water-stable aggregations or aggregates as determined by the wet-sieving technique previously outlined appear to be important indicators of the structural characteristics of the stabilized soils and should be related to the erosion test results.

Figure 19 provides "bench marks" for the two soils, that is, cumulative aggregate size distribution curves for soils which have not been treated with additives. The test does not distinguish between sand-size particles and water stable aggregations of finer particles. The Crosby soil contains significant amounts of relatively coarse sand and fine gravel particles and is clearly a significantly coarser material than the grundite, which has little sand and virtually no water stable aggregations coarser than about 0.5 mm in size.

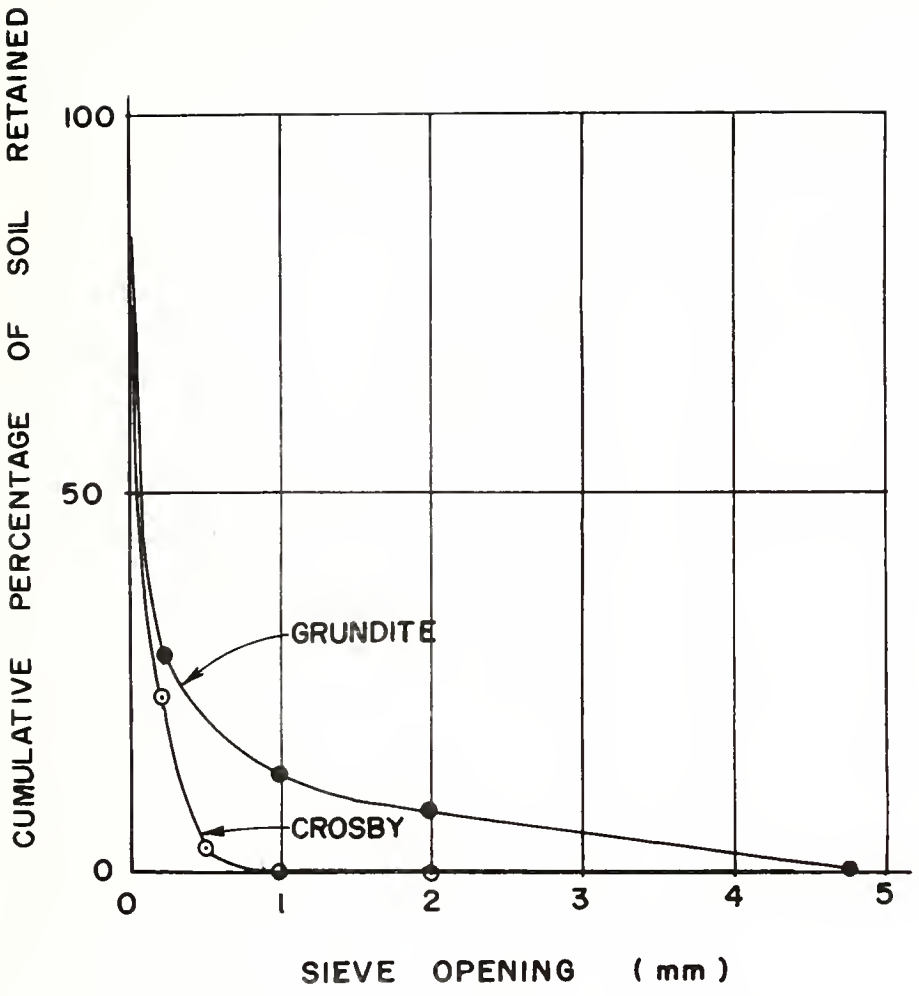


Figure 19. Cumulative size distributions of water-stable aggregates for untreated (additive-free) soils.

Analysis of the aggregate-size distribution of lime-stabilized soils

The influence on the aggregation of the Crosby soil of the addition of as little as 1 percent by weight of the pure lime is shown in Figure 20. Separate curves are given for the size distribution of the additive-free Crosby soil and of this soil treated with 1 percent lime and cured for 7, 14, and 21 days. As indicated in Figure 20, such treatment slowly increases the content of water-stable aggregates, particularly in the size range coarser than 2 mm. At a higher lime content (2.5 percent) much more aggregation occurs and the process is very much advanced even after as little as 7 days of curing, as indicated in Figure 21. By this time the content of water-stable aggregates is almost 50 percent of the whole soil. This increases only to about 65 percent after 28 days cure.

With the grundite soil the situation is somewhat different. Addition of the relatively low-grade commercial lime has been shown to be ineffective as an erosion stabilizing measure, even at the 5 percent treatment level (Figure 8), and the pH produced is inadequate for proper stabilization. Figure 22 shows the aggregate size distribution curves resulting from such addition. There seems to be some initial aggregate formation, but this is modest in extent, and was completed by 7 days, further curing showing no further increment.

Analysis of the aggregate-size distribution of cement-stabilized soils

Addition of 1 percent of Portland cement to the Crosby soil was found to be insufficient for stabilization except after prolonged curing. An indication that this addition is not particularly effective in generating aggregates is given in Figure 23, which gives aggregate-size

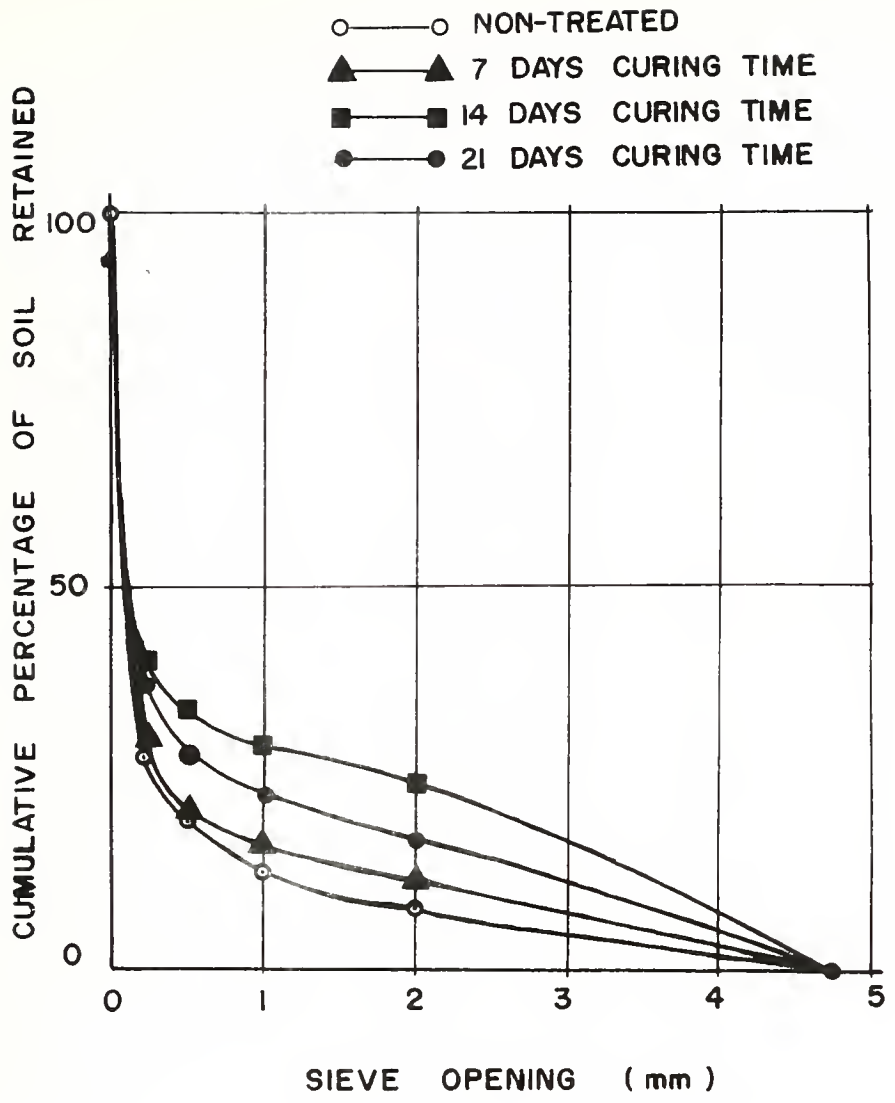


Figure 20. Cumulative size distributions of water stable aggregates of Crosby soil treated with 1% pure lime and cured for various periods.

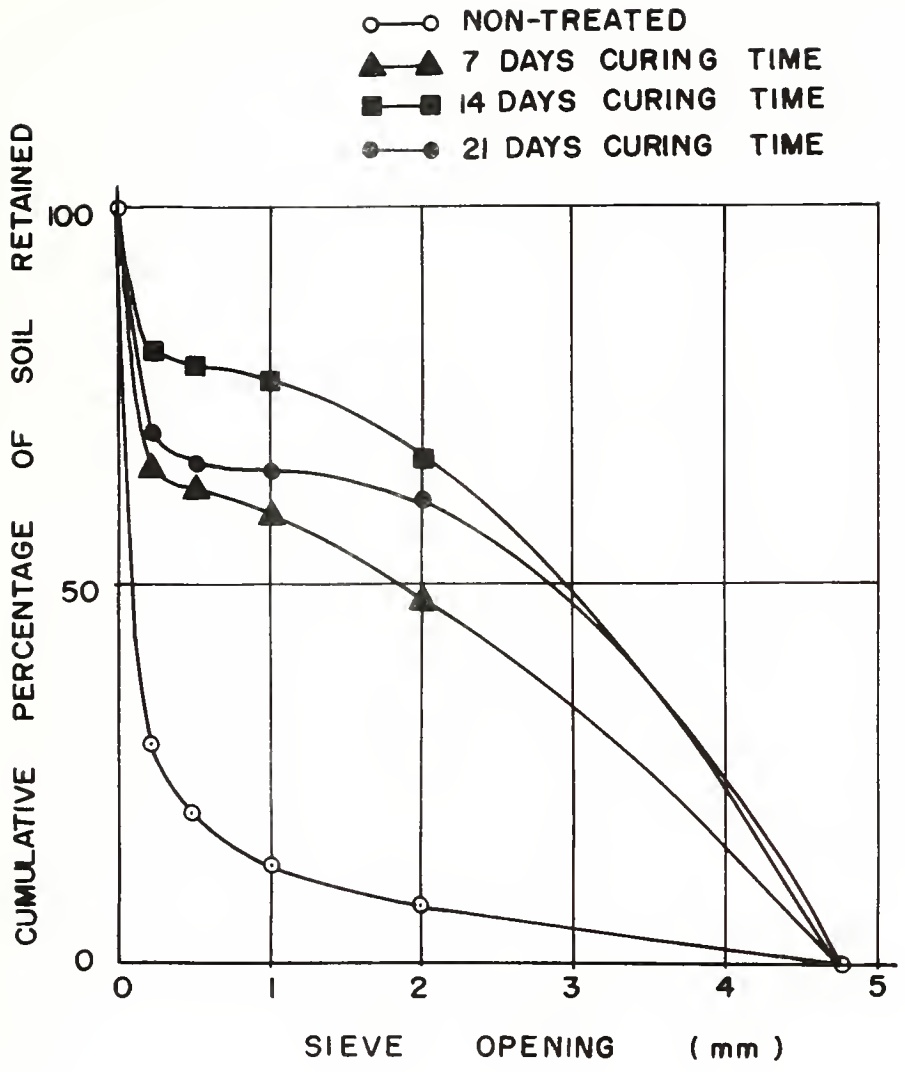


Figure 21. Cumulative size distributions of water stable aggregates in Crosby soil treated with 2.5% lime and cured for various periods.

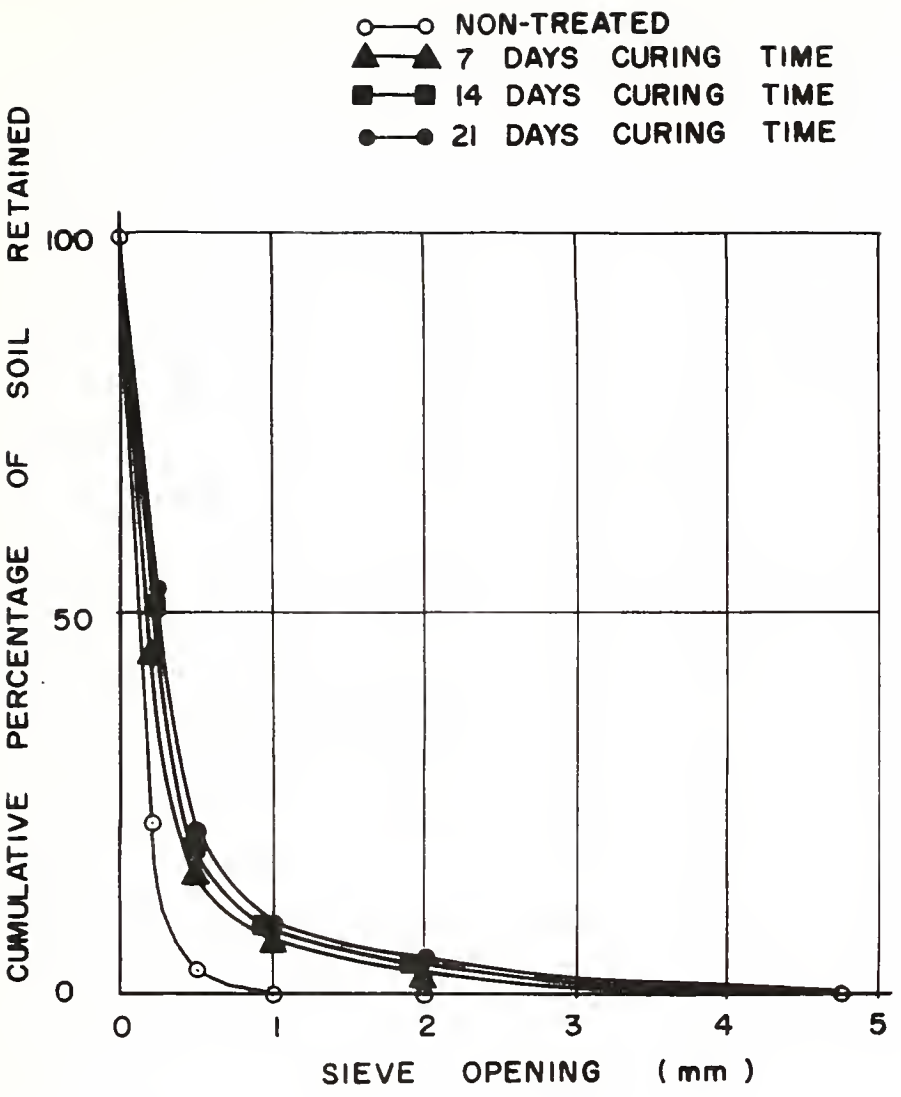


Figure 22. Cumulative size distributions of water stable aggregates in grundite soil treated with 5% of impure commercial lime and cured for various periods.

distributions after 1, 3, and 7 day curing periods. Only a modest degree of aggregate formation occurred. Similarly, grundite soil was not successfully stabilized with cement at the 2.5 percent treatment level, even after prolonged curing and as indicated in Figure 24, little aggregation occurrs with this combination. Treatment at the 5 percent level was found to be effective, however. Figure 25 confirms the rapid and nearly complete aggregation brought about by such treatment. Thus with cement as well as with lime, a successful stabilization against erosion loss is marked by the aggregation of a substantial proportion of the soil fines into water stable aggregations.

Possible use of "aggregation index"

An index to the extent of aggregate formation can be obtained from the results of the aggregate size distribution tests discussed above. The procedure is to calculate the so-called mean weight diameter (MWD), defined as the sum of the mean diameter of each size fraction times the weight proportion of the whole sample in that fraction, the summation being carried out over all fractions including the one passing through the finest sieve. The "aggregation index" is defined by subtracting from this mean weight diameter the mean weight diameter of the original untreated soil (4).

Unfortunately, attempts to use this concept in interpretation of the present results did not lead to any consistent pattern or relationship between aggregation index and stability to rainfall erosion. Thus potential utility of this measurement is left to future investigation.

Pore-size distributions of stabilized soils

Determinations of pore-size distributions of untreated and of treated soils were carried out by standard mercury porosimetry methods to explore

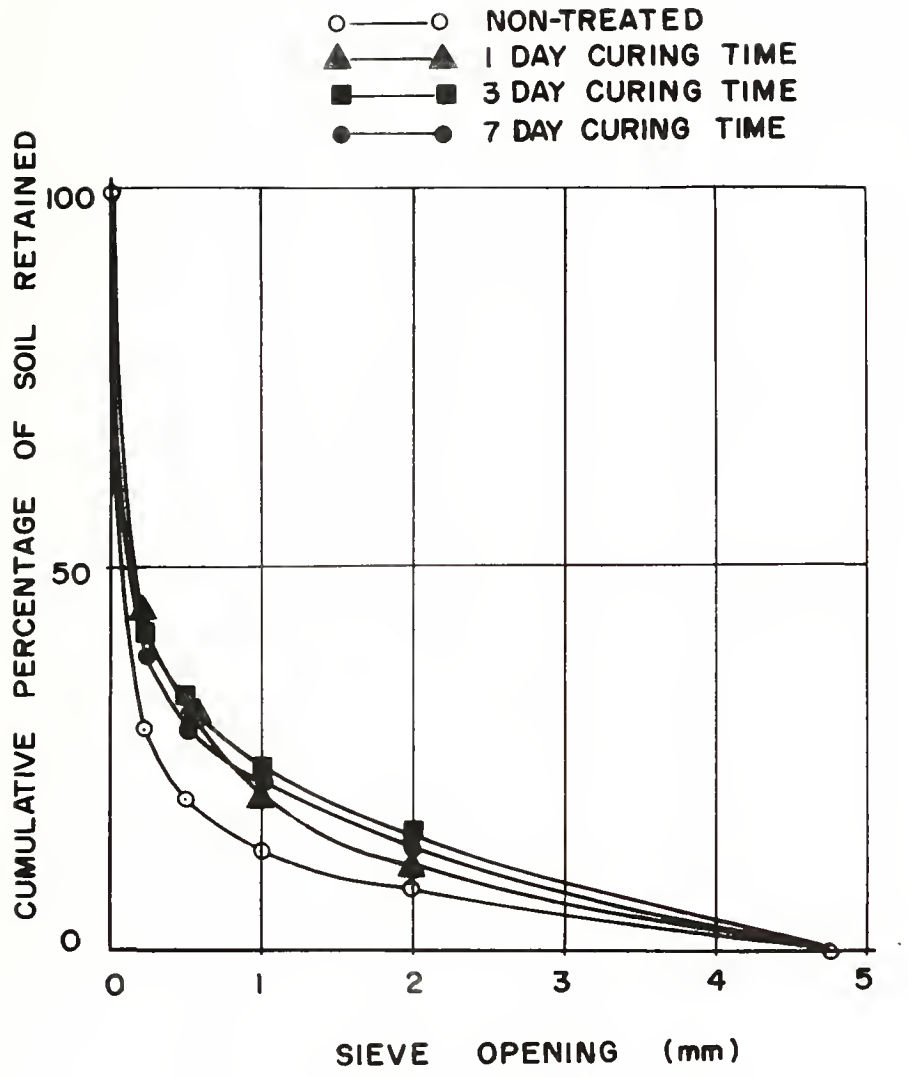


Figure 23. Cumulative size distributions of water stable aggregates in Crosby soil treated with 1% Portland cement and cured for various periods.

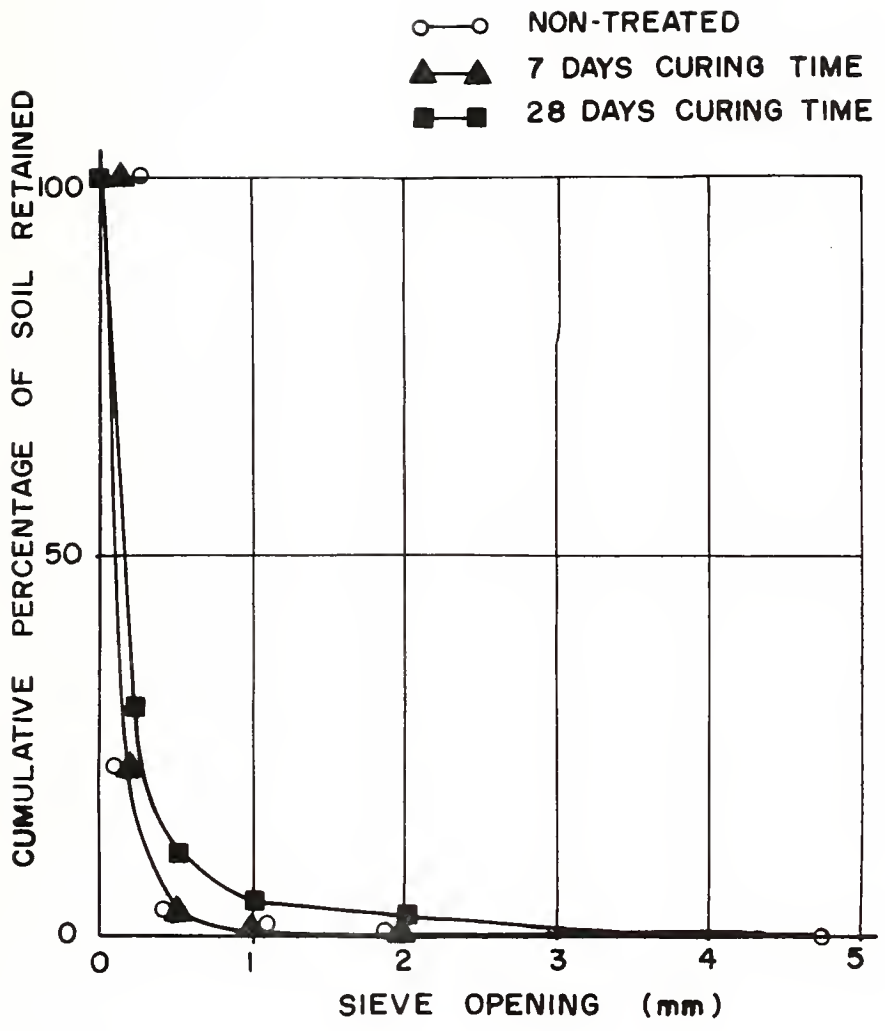


Figure 24. Cumulative size distributions of water stable aggregates in grundite soil treated with 2.5% Portland cement and cured for various periods.

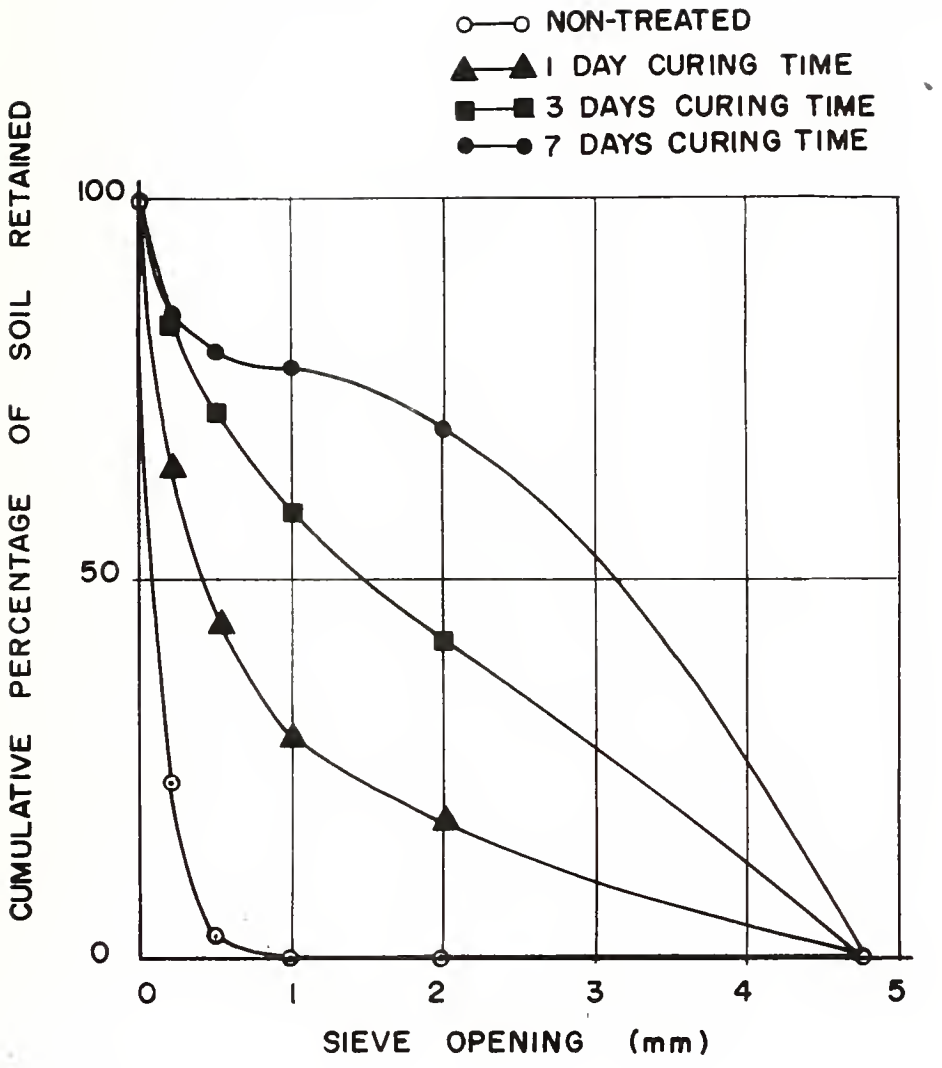


Figure 25. Cumulative size distributions of water stable aggregates in grundite soil successfully stabilized with 5% Portland cement and cured for various periods.

the extent to which this characteristic might shed some light on the microstructure of stabilized materials and upon any changes in microstructure taking place as a result of exposure to the test rainstorms.

Specimens were secured by carefully fracturing representative portions of the material subsequent to oven drying, and reflect any changes that such pretreatment produces. Previous investigations have indicated that such changes are comparatively modest for well compacted grundite clay, and it is reasonable to suppose that the Crosby soil will behave in a similar fashion. The size of specimen for which this technique is practical is of the order of 0.5 to 1 gram, and local sample variation is something of a problem. Two replicates were run for each determination, and in most of the figures both are given, along with a mean curve. This study was unusual in that specimens were also taken from the exposed surface zone remaining after exposure to the rainstorms, with a view toward evaluating any gross changes taking place as a result of such exposure.

An indication of what occurs with successfully stabilized soils is given in Figure 26, which represents the results for Crosby soil. The additive-free soil, as compacted (and oven dried) shows a total porosity available to mercury at the maximum pressuring capacity of 15,000 psi as about 0.18 cm^3/g of soil. Most of this is in pores of a range between about 10 micrometers and 0.3 micrometers, a distribution reasonably common to many compacted soils of moderate clay content (5). Specimens prepared from the top portion of the additive-free soil after exposure to rainfall (and subsequent oven drying) shows a total incrusion of about 0.22 cm^3/g. of soil, a modest increase. Essentially all of the increase

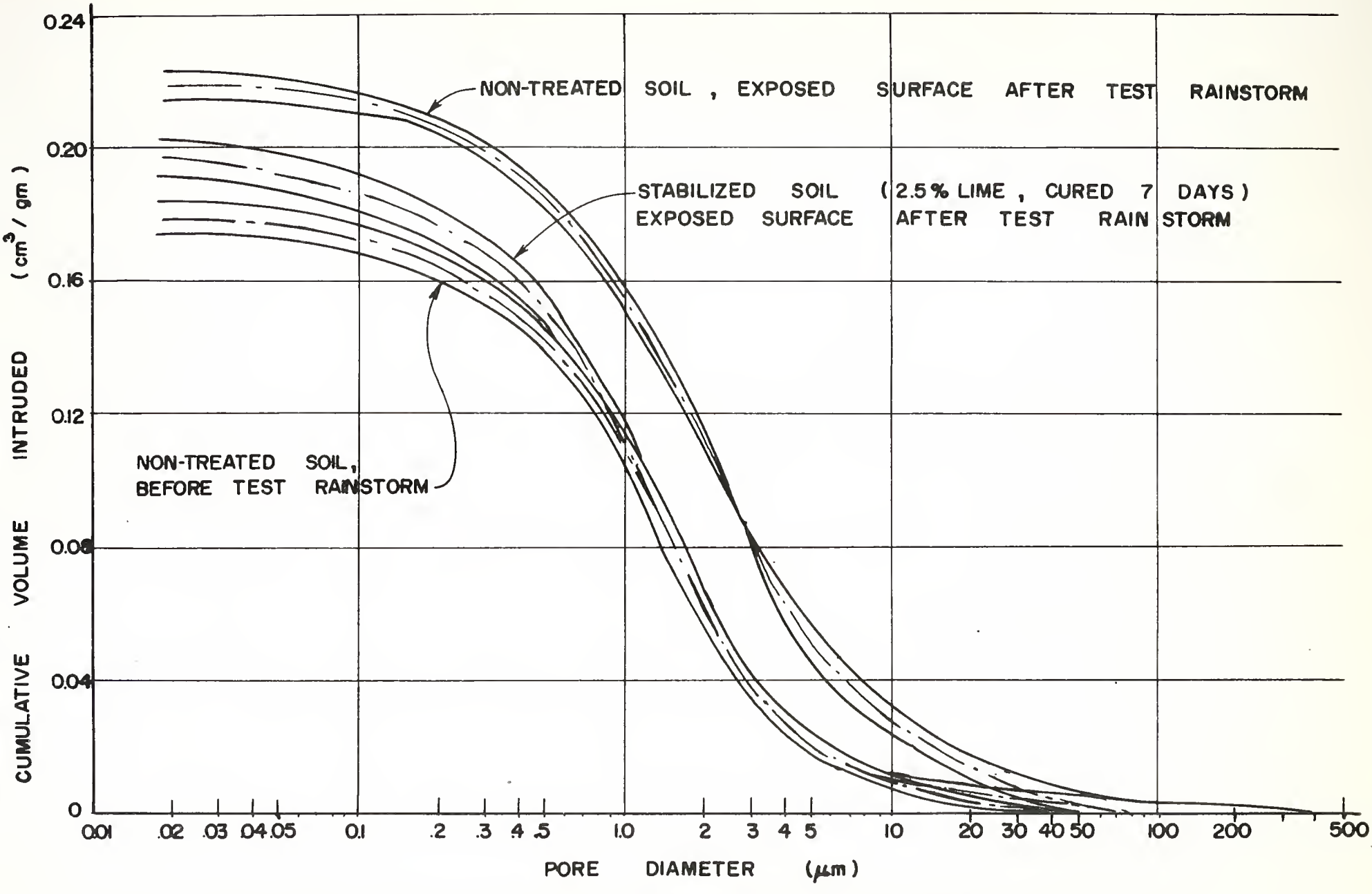


Figure 26. Pore size distributions for Crosby soil specimens.

represents pores between 5 μm and 40 μm, i.e., the relative coarse part of the distribution, and presumably represents space left by washing out some of the weaker, unstable naturally-occurring aggregations of particles near the surface, plus whatever influence of swelling might be that took place under the essentially saturated conditions.

Figure 26 also includes a distribution curve for a specimen treated with 2.5 percent lime, cured for 7 days, then exposed to the test rainstorm. Reference to results cited earlier indicates that such material was effectively stabilized against soil erosion, having a loss of only 0.2 g/cm^2 of exposed surface (Figure 3). In this case the pore size distribution is very much like that of the untreated compacted soil before rainfall exposure, the only apparent difference being a modest (0.02 cm^3/g) increase in pore space in the size region below about 0.8 μm. Thus there is only minimal rearrangement under the influence of the test rainstorm. In short, for all practical purposes, the pore size distribution of a propertly stabilized soil does not undergo significant change when exposed to rainfall.

Figure 27 shows median integral pore size distribution curves (i.e., "running averages" of two replicates) for grundite soil specimens of several kinds. The solid line represents additive-free grundite; the line composed of long dashes is grundite with 2.5 percent of the impure commercial lime added and cured for 1 day; the line composed of alternating dashes and dots represents the same material cured for 14 days; and the short dotted line represents grundite mixed with 5 percent of the same line and cured 1 day. While there are differences between the lines they are all similar, and the variations are of the same order of magnitude as variations between replicate specimens of the same material, and so are not of significance. Apparently as much as 5 percent can be added without

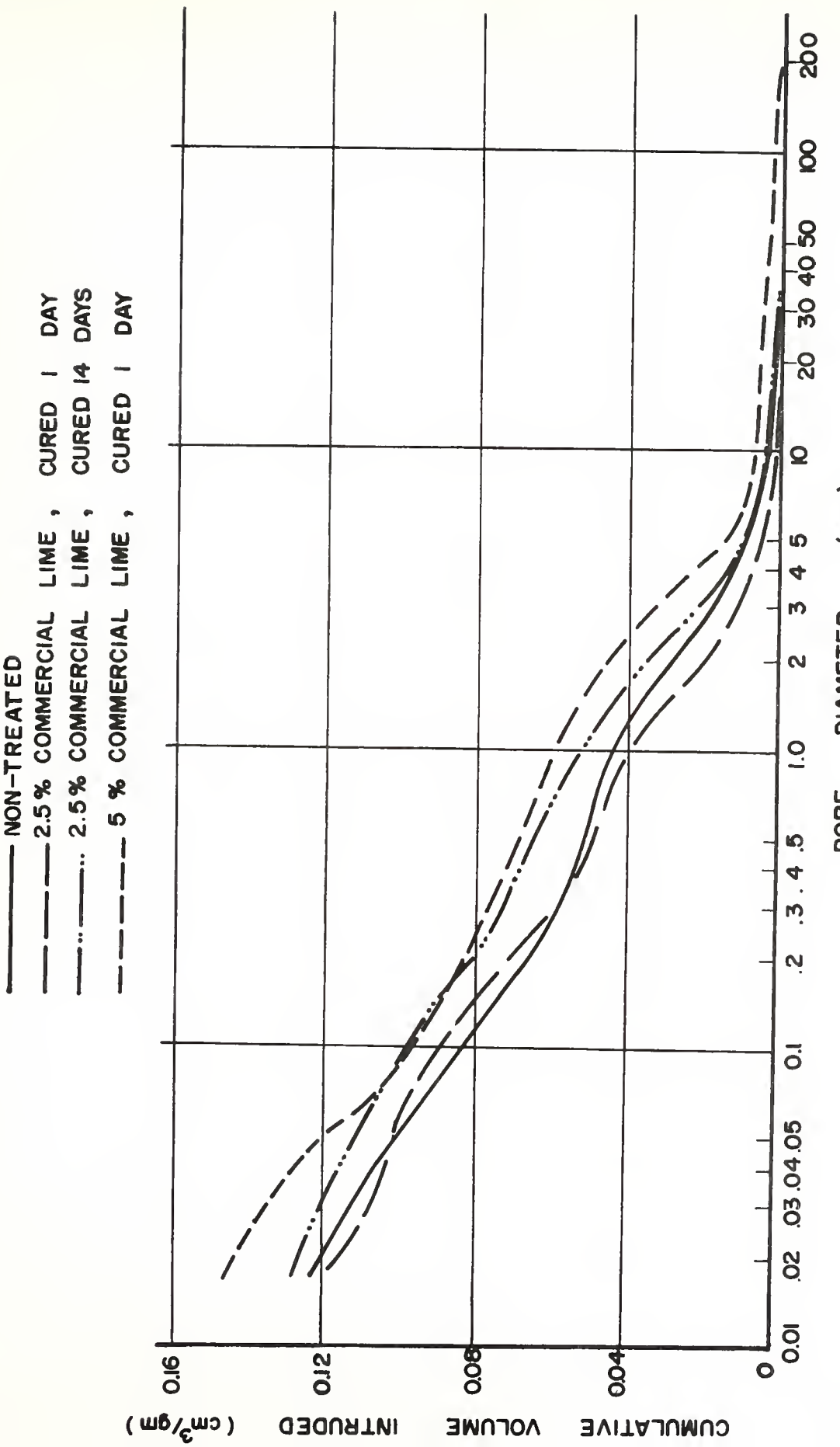


Figure 27. Pore size distributions for grundite soil specimens not exposed to rainfall.

changing the pore size distribution of the compacted clay very much.

Figure 28 gives replicate distributions for additive free grundite before exposure to rain, and for specimens cut from the new surface of this material after rainstorm exposure. Unfortunately, the variation between replicates is considerable. However, it is clear that there is no pronounced difference between the two sets of data, that is, exposure to the rainstorm and consequent erosion has not changed the pore structure of the underlying material newly exposed on the surface. This is quite different from the results of Figure 27 for Crosby soil, where a definite increase in pore volume was observed in the coarse pore size range. The reason for this difference will be discussed subsequently.

Figure 29 holds part of the key to understanding the "destabilizing effect" associated with use of the lime or cement in inadequate amounts with grundite soil. The soil specimens under consideration were treated with 2.5% Portland cement and cured for 14 days. As indicated in Figure 15, the loss on erosion amounted to 2.4 g/cm^2 of exposed surface, considerably more than that lost by grundite alone (1.7 g/cm^2). It was found that little formation of water-stable aggregates took place with such specimens (Figure 24), and that the pH of such a mixture rose only to 10.5 inadequate for cementing reactions to occur.

As indicated in Figure 29, the pore size distribution for specimens of this material before exposure to rainfall is essentially indistinguishable from those of other compacted grundite specimens, and shows a cumulative intrusion of the order of 0.13 cm^3/g. In contrast, the residual exposed surface region of the material left after exposure to the

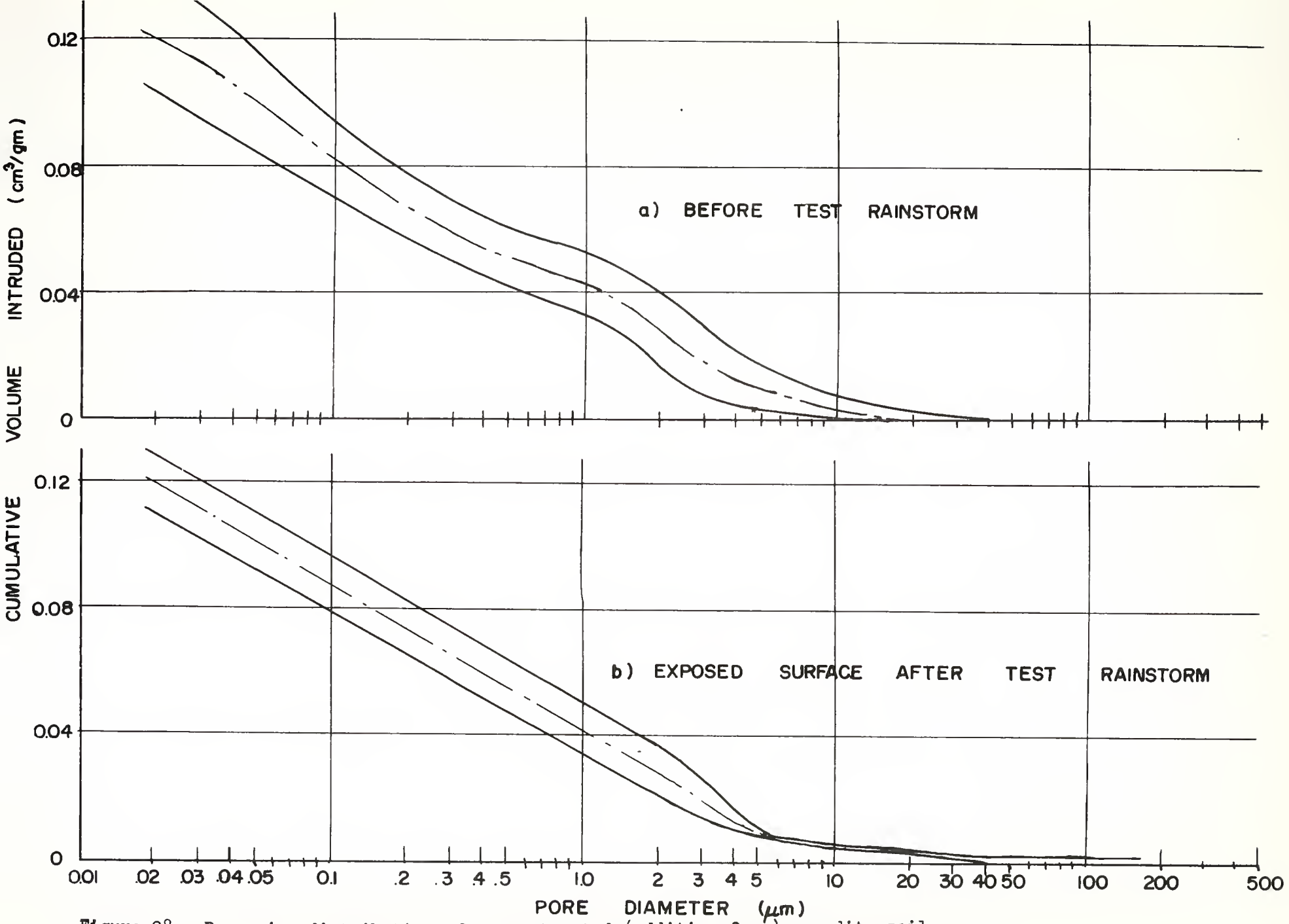


Figure 28. Pore size distributions for non-treated (additive-free) grundite soil.

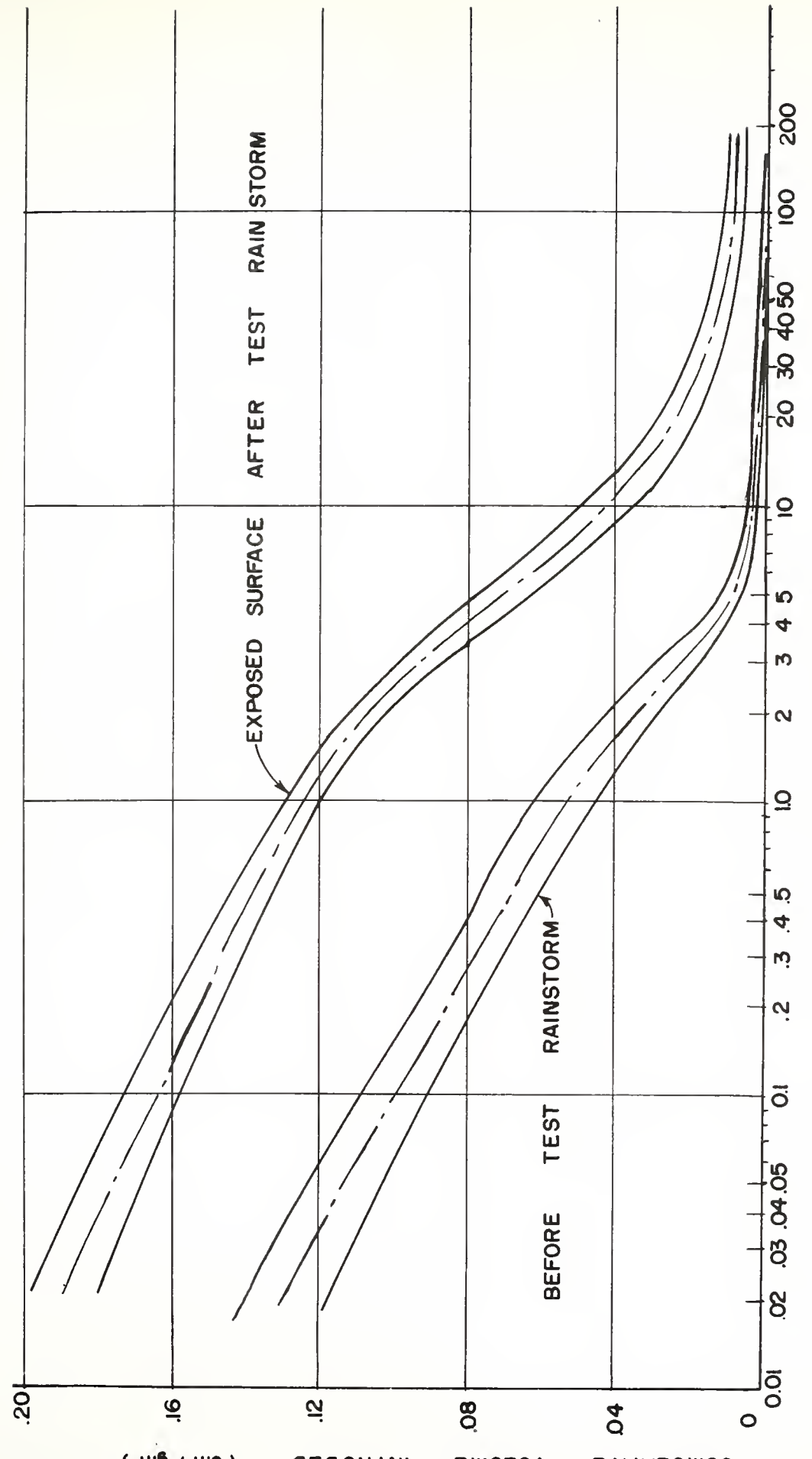


Figure 29. Pore size distributions for grundite soil "destabilized" by treatment with 2.5% Portland cement and cured for 14 days.

test rainstorm has a cumulative intrusion of nearly 0.20 cm^3/g. The extra pore space is almost entirely located in the coarse pore region of the spectrum, from roughly 5 μm to as large a size range as can be tallied, roughly 200 μm. This radical difference in pore-size distribution implies a major rearrangement of the microstructure, leaving enhanced volumes of large accessible voids. Such a picture is consistant with breakdown of the preexisting quasi-stable aggregation of the soil particles present in the acid-flocculated dry or compacted material. In this view, the moderately elevated pH derived from lime or cement additon is enough to permit easy breakdown of the aggregates in the zone under exposure to rainfall impact and local moisture saturation. This breakdown does not occur in additive-free grundite exposed to the rainstorm, since there the local pH remains acid, and only mechanical breakdown or removal of whole aggregations can occur.

The Crosby soil, being less aggregated and not acidic at the outset, normally undergoes some breakdown and at least some increase in porosity as it becomes exposed to the rainfall impact. Presumably, this is the normal state of affairs with most soils, and the response of the grundite is to be considered unusual.

Scanning electron-microscope observations

A preliminary study was carried out on the grundite soil to attempt to document morphological detail of the surfaces of the soil before erosion and after erosion.

As indicated in Figure 30a, taken at an original magnification of 60x, the soil surface originally presented to the rainfall is quite

Figure 30a. Scanning electron micrograph of fresh, uneroded surface of additive free grundite before exposure to test rainstorm.

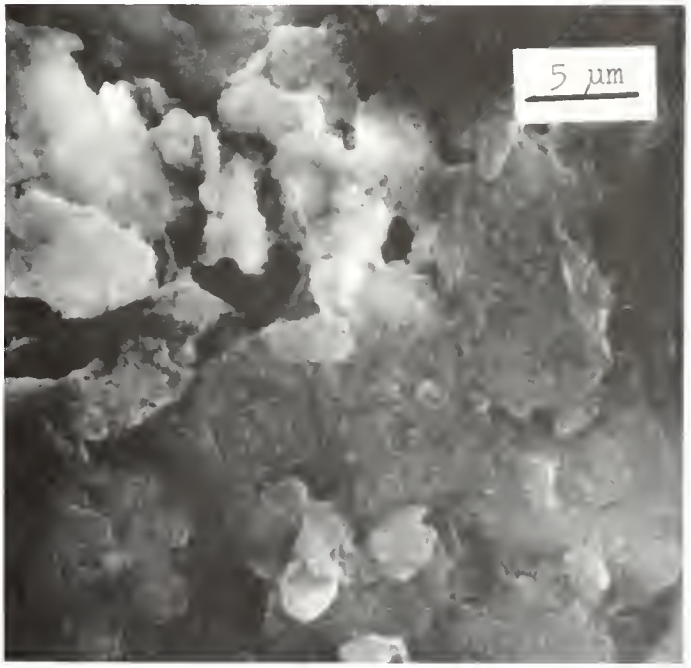


Figure 30b. Higher magnification micrograph showing clay particle morphology and arrangement.

smooth in many areas, although there are many breaks in the surface and occasional clay particles positioned above the general surface level. That the surface is actually far from a homogeneous solid mass is clearly brought out by Figure 30b, which shows a portion of the same area at higher magnification (originally 3,000x). There seems to be a partial "skin" or oriented clay particles, but it is quite incomplete. Even the areas of "skin" are far from smooth on this scale, having corners and even small clay "dust" particles clinging to the surface. More important, the areas left open (upper left and bottom portions of the micrograph) show a very porous structure with many loose individual clay particles and some aggregations of particles visible. What cannot be seen at the surface is the underlying structure of compound aggregations, the largest of which are several hundred μm across, that makes up the bulk of the structure.

When this surface of unstabilized clay is exposed to a rainstorm it is rapidly removed by raindrop impact, and the underlying structure of the material is exposed, as is visible in Figure 31a. This micrograph shows these remnant quasi-stable aggregations, clearly outlined by the probable removal of loose particles that existed in the boundary zones between them. Apparently in the process of erosion these aggregations may be broken down to smaller sizes, such as are visible in the lower left portion of the micrograph, and removed without dispersion. Figure 31b reveals the underlying arrangement of individual clay particles that goes up to make up one of these large aggregations.

An illustration of the appearance of the surface of a "destabilized" grundite specimen after exposure to a test rainstorm is given in

Figure 31a. Scanning electron micrograph of eroded surface of additive-free grundite after exposure to the test rainstorm.

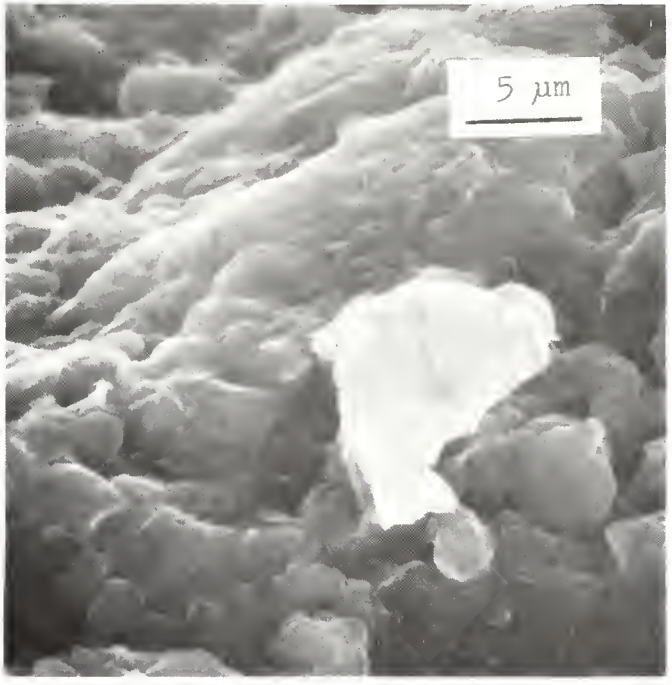


Figure 31b. Higher magnification micrograph showing clay particle morphology and arrangement.

Figure 32, which represents such a surface of a grundite treated with 5 percent of the impure commercial lime and cured for 6 days prior to exposure. While it is difficult to draw definitive conclusions from single micrographs, it does appear that there is considerably greater breakdown of the aggregations into either single clay particles or small clusters of particles in such a surface as compared with the corresponding surface of an additive free grundite, Figure 31a. At higher magnification, as shown in Figure 32b, one can observe a considerable tendency toward the partial detachment of individual clay particles.

Grundite stabilized with cement apparently retains the smooth but incomplete surface layer that is characteristic for compacted additive-free grundite, at least before exposure to rainfall. Figures 33a and 33b record the appearance of such layers at moderately high magnification, for a specimen of grundite treated with 5 percent Portland cement and cured for 10 days.

When such well-stabilized specimens are exposed to rainstorms, there is apparently no loss of material from most of the surface. As seen in Figure 16 (left hand photograph) erosion, if it takes place at all, is confined to the rim of the specimen. Examination of the flat "pavement area" after exposure to rainfall reveals a dramatic change of morphology As shown in Figure 34a, the surface now has an incomplete layer of blocky, angular particles several μm in size. Some of these, on close examination, appear to be rounded, and more strangely, some of them display what appear to be relatively large holes, ranging from perhaps half a μm to several μm in diameter. As indicated in Figure 34b, examination at higher magnification confirms these holes, and displays the

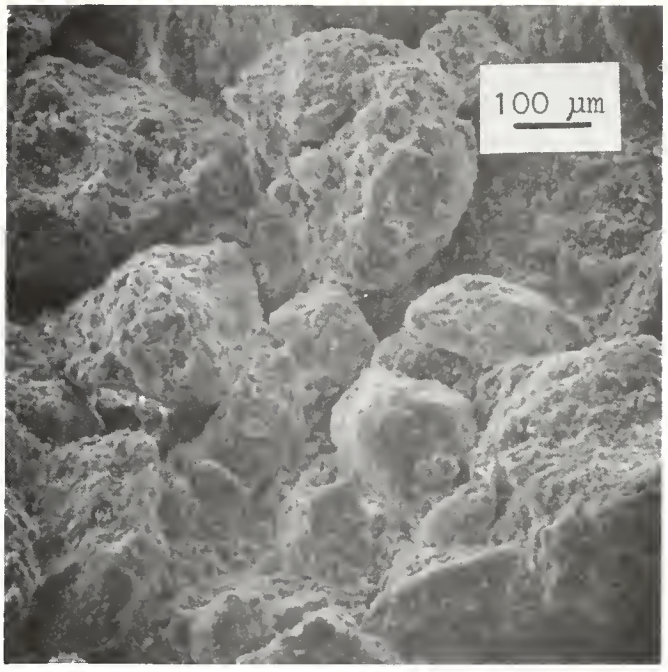


Figure 32a. Scanning electron micrograph of eroded surface of grundite treated with 5% of impure commercial lime and cured 6 days before exposure to test rainstorm.

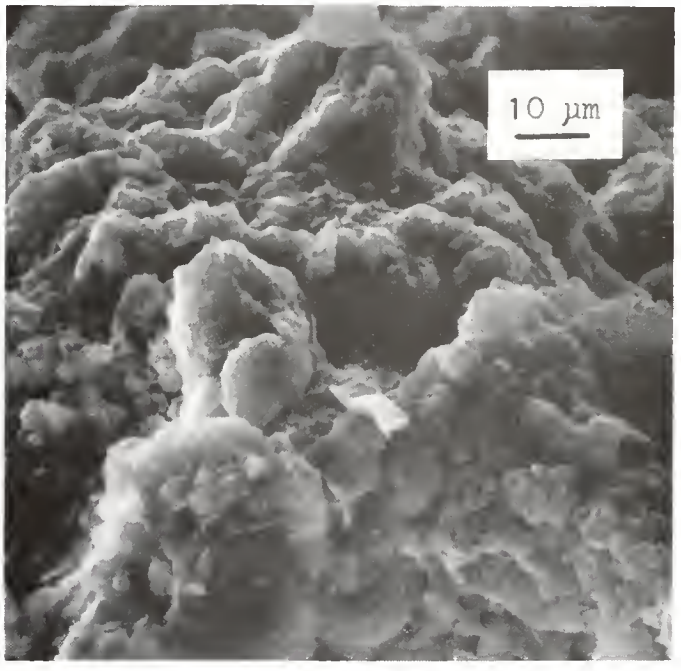


Figure 32b. Higher magnification micrograph showing partial detachment of individual clay particles.

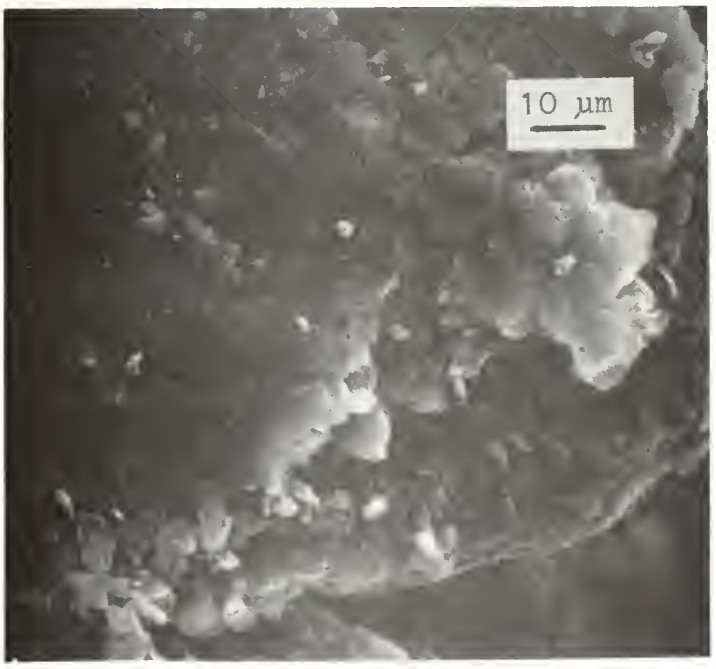


Figure 33a. Scanning electron micrograph of fresh, eroded surface of grundite stabilized with 5% Portland cement and cured for 10 days.

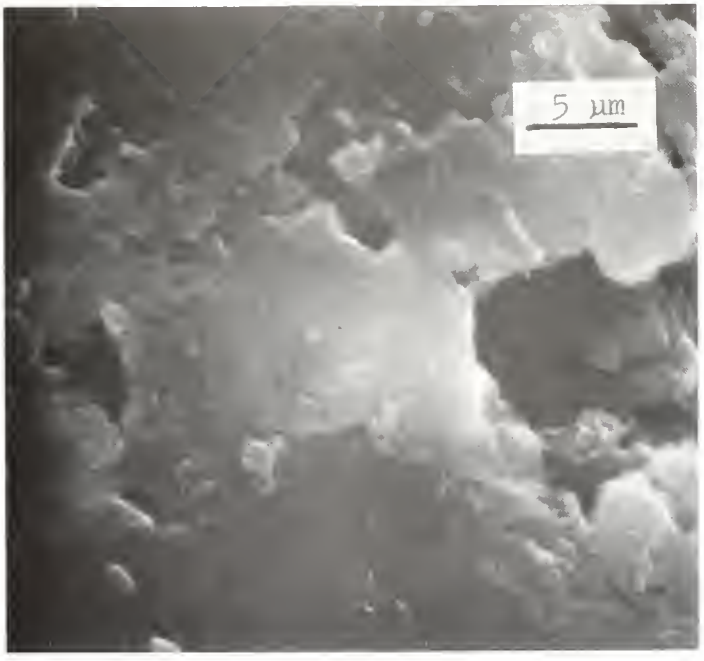


Figure 33b. Higher magnification view showing details of particle orientation in surface layer.

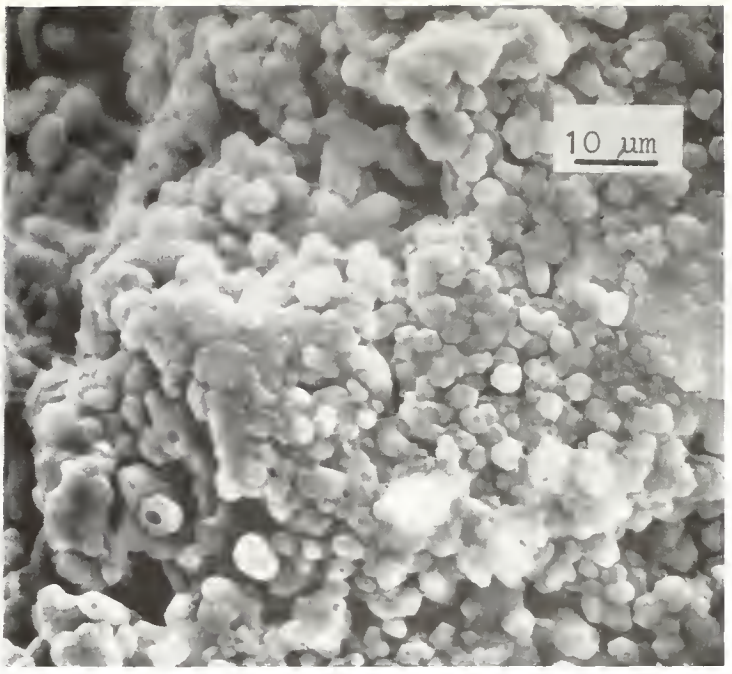
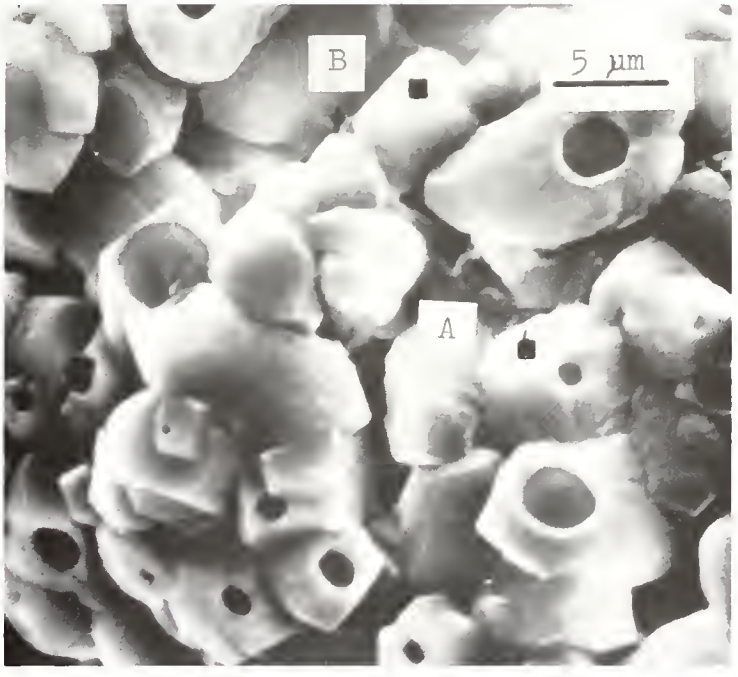


Figure 34a. Scanning electron micrograph of eroded surface of grundite stabilized with Portland cement (5%) and cured 7 days before exposure to test rainstorm.



Eigure 34b. Higher magnification micrograph of area above. Markings labeled "A" and "B" are spots selected for energy dispersive x-ray spectrometric analysis.

morphology of these apparently erosion-resistant particles more clearly. Some of the particles appear to be well-delineated single crystals with sharp edges and plane faces; others give the impression of being stacks of plates, perhaps of the original illite clay, and presumably in process of chemical transformation.

To check these impressions the electron beam was focused in the stationary mode on two typical particles, designated "A" and "B" in Figure 34b, and x-ray spectra were collected using an EDAX Inc. energy-dispersive x-ray spectrometer. Examples of the spectra collected are given in Figure 35.

Figure 35a is a spectrum for site A of Figure 34, a rounded particle with a prominent hole and a relatively rough surface suggestive of its origin as an aggregation of clay particles. The spectrum shows prominent peaks at 1.71 keV and 1.45 keV, indicative of silicon and aluminum respectively as major constituents, as they are of the aluminosilicate clay mineral illite. There are substantial peaks at 3.7 keV; testifying to the presence of a significant calcium content. Other peaks present are those for potassium, a minor constituent of illite clay, at 3.3 keV; iron, another minor clay constituent, at 6.4 keV; and gold, used in coating the specimen, at about 2.2 keV.

Figure 35b, showing the spectrum generated at site B of Figure 34b, indicates a much different chemical composition. The only peaks observed are those for calcium and for the gold coating. It appears that the particle labeled B and by extension, others showing the same crystalline morphology, are calcium carbonate.

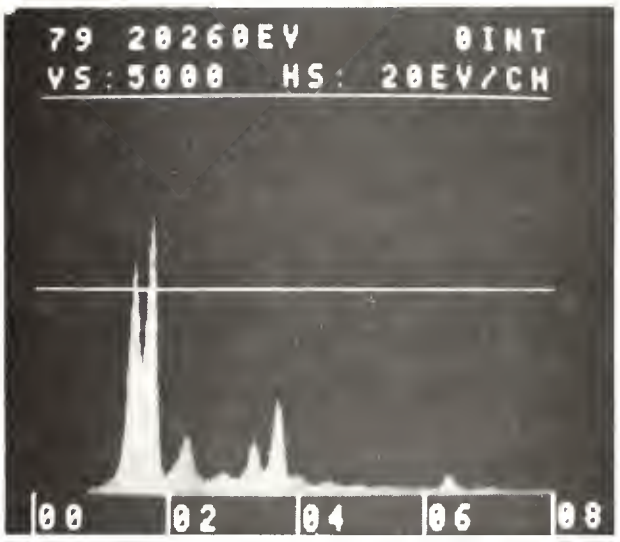


Figure 35a. Energy-dispersive x-ray spectrum for spot labeled "A" of Figure 19b.

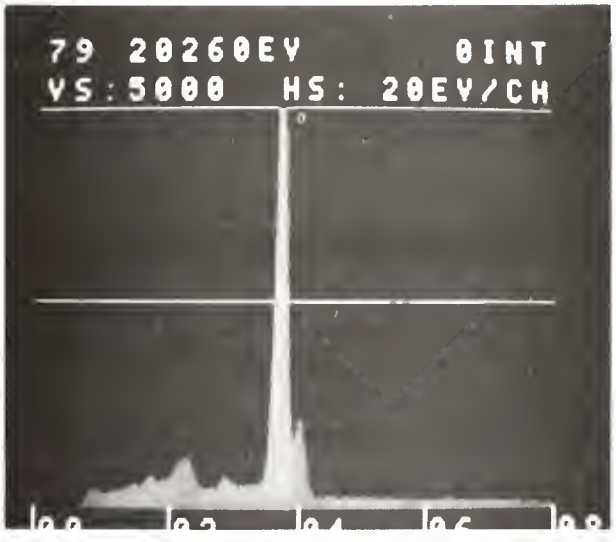


Figure 35b. Energy-dispersive x-ray spectrum for spot labeled "B" of Figure 19b.

Indications that this is so were obtained from x-ray diffraction patterns secured from powder scraped from the surface layer of this specimen. Prominent calcite (calcium carbonate) diffraction peaks were detected by this technique.

It also appears that in this case the calcite crystals are formed at or near the "pavement" surface of the specimens during the rainstorm itself, since the surface of similar specimens not exposed to rainfall do not show these at all, as indicated in Figure 33. Furthermore, x-ray diffraction patterns of powder scraped from the surface of such specimens do not show calcite peaks. They do, however, indicate the presence of calcium hydroxide, presumably generated by the cement hydration reactions. Presumably the wet condition obtained during the rainstorm facilitates the conversion of previously unreacted calcium hydroxide to calcium carbonate.

Such crystals are not confined to the flat, uneroded portion of the surface but are also found to be present on the residual surface of the eroded rim. An illustration of this is indicated in Figure 36, which represents the rim portion of a similar specimen cured for 13 days prior to exposure to the test rainstorm. Furthermore, given sufficient exposure, such crystals may even appear on fractured surfaces, i.e., surfaces not exposed to rainfall. An illustration of such an occurrence is given in Figure 37, which represents the fracture surface of a specimen of grundite stabilized with 5% lime and cured for 28 days.

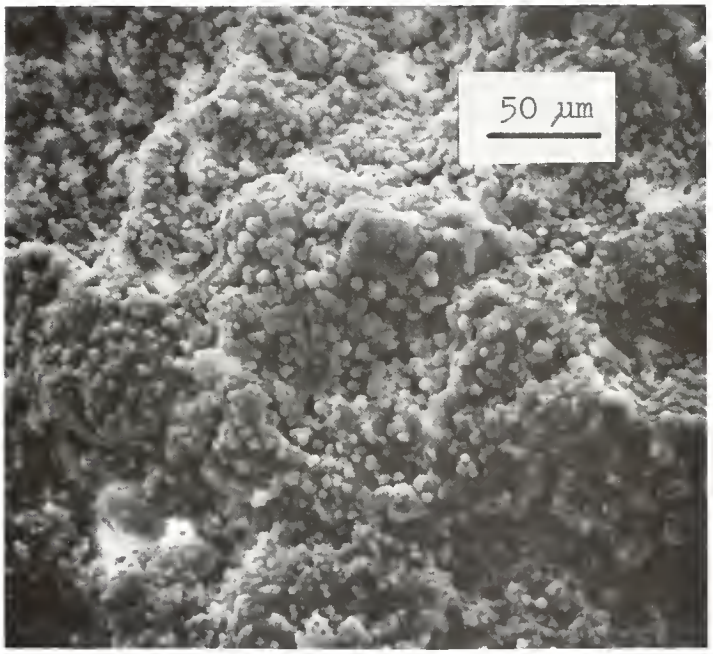


Figure 36. Scanning electron micrograph of rim area of grundite stabilized with 5% Portland cement and cured 13 days prior to exposure to test rainstorm.

Figure 37a. Scanning electron micrograph of grundite specimen stabilized with 5% Portland cement and cured for 28 days. The surface is a fracture surface.

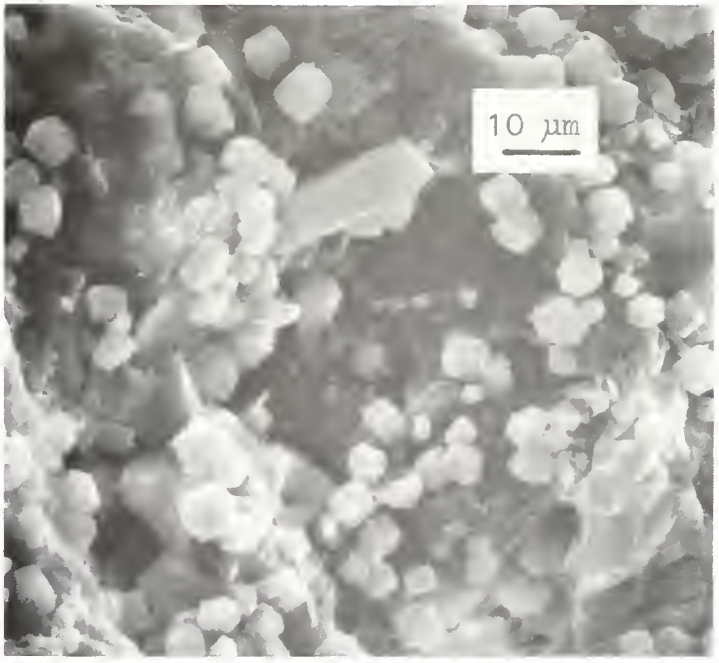


Figure 37b. Higher magnification view of the same surface.

The existence of the calcium carbonate is not, however, likely to be important in the stabilization process. What is of far more consequence is the generation of calcium silicate hydrate gel (C-S-H gel) both by hydration of the cement, and by reaction of some of the lime deposited by the cement hydration reaction with soil particles. Such gel does act to bind together individual aggregations of clay, or of reacting clay particles into a reasonably well knit framework which should resist erosion.

Illustrations of gel forming such interparticle linkages are given in Figure 38, which represents the eroded surface of a grundite clay specimen stabilized with 5 percent Portland cement and cured for 13 days prior to exposure to the test rainstorm. The area pictured is on the slightly eroded rim of the stabilized specimen. The linkages are presumably the reticulated network form of calcium silicate hydrate gel (10), generated by hydration of the cement.

The exact mechanisms of the stabilization attained in this manner is a subject requiring extended study, and the present information is preliminary in nature. Nevertheless it is clear that the process does involve some conversion of clay to calcium-bearing reaction product, generation of some normal cement hydration product some of which links together individual aggregations, and at least during the rainstorm sequence, effective carbonation of the exposed calcium hydroxide generated by the cement hydration and not previously otherwise reacted with the clay.

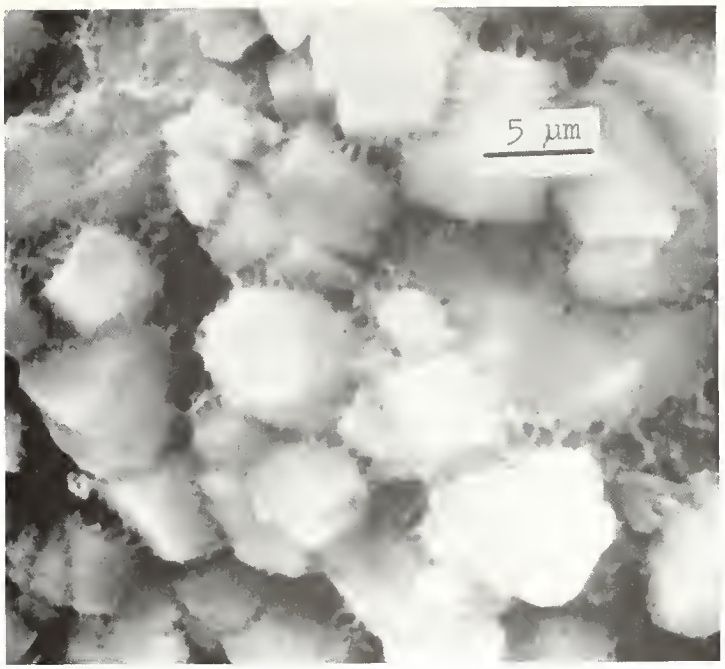


Figure 38a. Scanning electron micrograph of eroded rim portion of the surface of a grundite specimen stabilized with 5% Portland cement and cured for 13 days prior to exposure to the test rainstorm.

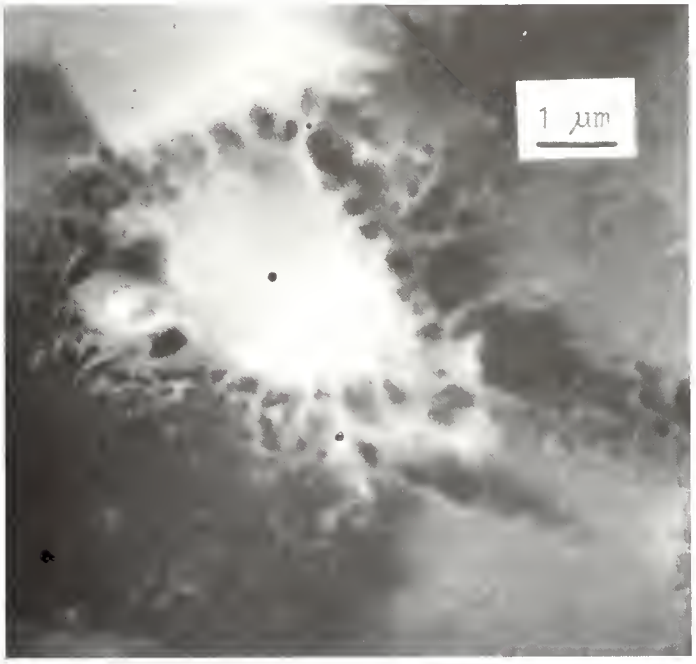


Figure 38b. High magnification detail of a similar area showing the reticulated network C-S-H gel linking adjacent particles.

Comparison of erosion loss with stabilized soils with that of soil protected by dense grass cover

It has been made clear in the preceding sections that stabilization of normal soil with lime or with cement can be accomplished readily at low percentages, and that such stabilized soil suffers only modest loss of soil under the test rainstorm, generally less than 0.2 g soil per cm^2 of exposed surface. This figure amounts to approximately 9 tons per acre on the basis of a direct conversion. However, since nearly all of this loss occurs in a rim around the perimeter of the specimen, it appears that a straight forward conversion would be misleading, and that a large area stabilized in the same way, because of the absence of easily-attacked edges corresponding to the rim of the specimens used here, would suffer much less soil detachment. On the other hand, a large area such as is exposed under field conditions would also suffer possible erosive loss due to running water, a situation not evaluated in the present tests.

Because of these uncertainties, any test relating the present results to field conditions would be of great interest.

One such simple comparison can be made. One of the most widely used forms of stabilization for erosion control involves planting grass, particularly tough sod-forming species, on slopes and areas not otherwise covered with pavement or other structures. It is certainly of interest to compare the loss of soil from such areas with that found to occur in the rainfall tests of stabilized specimens.

In order to make such a comparison special specimen holders of greater depth than those used in the experiments with stabilized soils were fabricated, and replicate specimens of Crosby soil were compacted into

these holders under standard compaction conditions corresponding to those used for the stabilized soil specimens. Following this, the top surface was scarified to a depth of approximately 1/2 inch, and Alta fescue grass seeded thickly on the surface. The surface was kept moist, and a stand of grass developed and was allowed to reach 3 inches in height before cutting. Subsequently the grass was kept hand trimmed to approximately 2 inches, to encourage development of a turf. After approximately 3 months the resulting thickly-turfed specimens were exposed to the standard rainstorm.

The appearance of the specimens after the rainfall exposure is illustrated in Figure 39. The grass is substantially matted from the force of the rainstorm, and is seen to cover essentially all of the surface of the specimen. Soil loss averaged 0.50 g/cm^2 of exposed surface. This is seen to be very much greater than that which could be characteristic of the same Crosby soil stabilized with small amounts of lime or cement. For example, 2.5% lime resulted in a loss of only 0.1 g/cm^2 in only 7 days, and the loss would be much lower than this after several months. With cement, a 2.5% treatment cut the loss to essentially zero (about 0.02 g/cm^2) in 1 day, and even a 1 percent treatment resulted in a loss of only 0.5 g/cm^2 by 28 days.

It seems clear then that the lime and cement treatments actually confer a highly satisfactory degree of resistance or prevention of soil detachment and loss under the severe conditions chosen for the rainfall test. A thick grass cover under the same test conditions does an appreciably poorer job of preventing soil loss, and of course such a cover requires proper climatic conditions and several months of elapsed time to develop.

Figure 39a. Specimens of Crosby soil stabilized with grass after exposure to the test rainstorm.

Figure 39b. Close-up photograph illustrating the degree of grass coverage of the specimen surface.

CONCLUSIONS

It is quite apparent as a result of the investigations described here that small quantities of Portland cement or of lime will stabilize a representative natural soil (Crosby) against all but a very small loss of soil when subjected to standardized severe rainstorm testing, involving more than 3 inches of rain per per hour on each of two successive days. The resistance measured is with respect to the detachment phase of soil erosion, resistance against erosion by running water not being a feature of the test program. Effective resistance against particle detachment is conferred within 1 to 3 days with cement and within a week with lime. Quantities as small as 1 percent may be effective.

It has been shown that the protection provided is distinctly superior to that accorded by a thick stand of Alta fescue grass.

Stabilization of an extremely acid soil material was found to require significantly more stabilizer. With this highly acid soil material, an impure, carbonated partly-dolomitic commercial lime even used at the 5 percent level was ineffective. Use of pure lime at this level was highly effective.

Considerable insight has been obtained on the mechanisms responsible for the development of the stabilizing effect, and of the mechanisms of particle detachment and removal from the soil.

It is recognized that the very favorable results secured were obtained by careful laboratory treatment involving thorough mixing, and careful compaction of the soil at the optimum moisture content. The

extent to which less stringent methods of incorporation (including spray or slurry application) and reduction or elimination of compaction may be tolerated without serious reduction in erosion resistance remain to be investigated. It is also recognized that the results described herein are limited to a single natural soil and a single commercial clay soil material: and tests are underway on a much broader range of soils.

POTENTIAL APPLICABILITY OF THESE RESULTS

While the conclusions obtained are subject to the limitations just enunciated, they are very encouraging with respect to potential practical application in temporary stabilization of exposed areas on construction sites. It is clearly established that with the soils tested, excellent stabilization can be attained. If similar results can be obtained on a wide spectrum of soils, and particularly if inexpensive and expedient methods of incorporating the stabilizers prove successful, the economics of providing protection in this manner appear to be quite favorable.

It must be kept in mind that specific testing of the effectiveness of such stabilization against running water erosion has not been made, although soil-cement made at higher cement contents has been successfully used for canal linings. Until such evaluation can be made, emphasis in potential applicability should be slanted to relatively flat areas and short slopes, especially if minimal lime or cement contents are to be employed. Conversely, if protection for long or for steep slopes are required, it should be feasible to provide such protection at added cost by specifying that higher than minimal lime or cement contents be used.

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